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DEVELOPMENT OF A PEBBLE-BED LIQUID-NITROGEN EVAPORATOR/SUPERHEATER FOR THE BRL 1/6TH SCALE LARGE BLAST/THERMAL SIMULATOR TEST BED, PHASE I: PROTOTYPE DESIGN AND ANALYSIS

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In the context of design studies for the U.S. Large Blast/Thermal Simulator (LB/TS) at WSMR, a liquid-nitrogen (LN_2) pebble-bed evaporator and superheater was designed for the 1/6th-scale LB/TS Test Bed at BRL. This pebble-bed heater would produce hot nitrogen gas at a predetermined temperature from a cryogenic LN_2 source at pressures up to 1700 psig. The flow rate would be sufficient to fill the driver tube of the BRL LB/TS Test Bed rapidly enough to minimize the heat losses through the uninsulated driver walls and to maintain the required nitrogen gas temperatures.

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The SPARTA principal investigator for the program was Dr. Irving B. Osofsky. He was assisted with design and testing by Gregory P. Mason and Michael J. Tanaka.

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1. INTRODUCTION

The following report documents the work performed in the Phase I effort of a three year program for the U.S. Army Armament, Munitions and Chemical Command (AMCCOM) Ballistics Research Laboratory (BRL) located at the Aberdeen Proving Ground, Maryland under contract DAAA15-87-C-0096 during the period 25 September 1987 through 24 September 1988. The contract is a three year research and development program entitled "Development of a Pebble-bed Liquid Nitrogen Evaporator/Superheater for the BRL 1/6th Scale Large Blast/Thermal Simulator". The objective of the program is to design, fabricate, test and deliver a liquid nitrogen (LN2) pebble-bed evaporator/superheater designed to supply pressurized heated nitrogen gas to the driver of the BRL 1/6th scale testbed of the Large Blast/Thermal Simulator at Aberdeen Proving Ground, Maryland. This report covers the design phase of the program. The pebble-bed evaporator/superheater rapidly evaporates high pressure cryogenic liquid nitrogen and controllably heats the resulting high pressure gas to a predetermined temperature for use in the shock tube driver.

2. BACKGROUND

The rapid growth of Soviet tactical and theater nuclear capability has increased the need to improve the nuclear survivability of U.S. tactical nuclear and conventional forces. The concern over nuclear survivability is reflected in Department of Defense (DoD) instructions and Army procurement regulations requiring specific nuclear hardness levels on military systems. There are within the Army alone over 150 systems with nuclear survivability requirements. At the present time, the U.S. lacks the simulation capability to test full scale systems to the full range of nuclear blast and thermal effects required. To answer this problem and reduce the cost of blast simulation, the Defense Audit Service recommended that the Defense Nuclear Agency (DNA) develop a Large Blast/Thermal Simulator (LB/TS). The U.S. Army Ballistics Research Laboratory has taken a leading role in research and development of LB/TS designs for DNA and the U.S. Army Harry Diamond Laboratory (HDL). This development of a Pebble-bed LN_2 Evaporator/Superheater is a continuation of the SPARTA/BRL development of the heated driver gas supply

as a part of a continuing program to develop a practical full scale LB/TS design.

The high pressure driver portion of the proposed LB/TS would use a parallel array of pressurized steel driver tubes to drive a blast wave in a large expansion tunnel by suddenly releasing the stored pressurized gas into the expansion tunnel. An artist's conception of a LB/TS facility is shown in Figure 2-1[1].

Earlier work performed by BRL and their contractors has shown that to simulate the higher shock overpressure and nuclear weapon yields of interest, it will be necessary to use high pressure gas stored in the drivers at pressures ranging to 2,200 psig (15 MPa). This gas must be heated to elevated temperatures as high as 700°F (644°K) in the driver tube array to provide the required simulation. The design pressure for the pebble-bed heater to be developed under this program was established at 2,200 psig.

In some earlier LB/TS design studies[2], several concepts were developed for providing high pressure, hot driver gas. These studies concluded that two types of gas pressurization systems are practical for the LB/TS; oil free reciprocating piston type air compressors with dehumidifiers and cryogenic reciprocating piston LN_2 pumps with vaporizers. Both of these systems provide the drivers with ambient temperature gas at high pressure. The studies also showed that the air compressor systems for the LB/TS would be very large and costly installations which would take in the order of 10-16 hours to pump up the LB/TS drivers. Also, the pressurized air produced by the compressors will have a sizeable residual moisture content, even with the best of air dryers. This moisture condenses in the expansion test section and produces dense opaque vapor clouds that obscures optical recording instruments and deposits moisture over the test item and the interior of the shock tube. In contrast, SPARTA has demonstrated that relatively small LN_2 pumping systems combined with pebble-bed evaporator/superheaters can be sized to provide the required maximum driver pressure and temperature conditions in less than an hour (even in 5-10 minutes if necessary) and the nitrogen gas produced by a LN_2 pumping/vaporizing system is pure and completely dry which results in clean cloudless tests with no obscuration of the optical data recording systems.

LARGE BLAST / THERMAL SIMULATION FACILITY

FIGURE 2-1 LARGE BLAST THERMAL SIMULATOR FACILITY CONCEPT (REF 1)

The previous studies (see Reference 2) have shown that heating of the driver gas can be accomplished by either of two schemes; heating during driver pressurization (single pass heatup) or heating ambient temperature gas after pressurization (bypass recirculation heatup). The first heating scheme can only be practically used with the LN_2 fill system because of the long compression/fill times associated with standard air compression systems. The second heating scheme can be successfully used with either driver fill system if the drivers are internally insulated, because heating takes place once the driver is pressurized. There are, however, two major problems associated with the design of heated gas drivers which use long fill time air compression systems and bypass recirculation heating.

The first problem is the rapid cooldown of the heated driver gas due to the very large heat loss from the hot driver gas to the steel driver tube walls. Unfortunately, conventional high temperature insulation materials will not survive the cyclic conditions of high temperature, high pressure followed by rapid decompression with accompanying negative pressures experienced in the LB/TS driver tubes. The development of a special insulation system which might withstand these adverse conditions is under study by BRL but there have been no test results to verify the structural integrity of the system.

The second problem encountered is the lack of available high pressure, high temperature, large flowrate gas bypass blower recirculation systems that can recirculate initially cold pressurized driver gas from the driver through a conventional heat exchanger and back to the driver to slowly raise the temperature and pressure of the gas to the required design condition. Furthermore, very large horsepower motors and gearboxes would be required to power the blowers. This means that the blowers, blower drive systems and heaters would have to be specially developed. This development of the circulation/heating system and the complexity of the valving and piping required to operate a bypass heating system would make building the bypass system extremely costly and technically risky.

The concept of using pressurized LN_2 as the source for the LB/TS hot compressed

driver gas utilizes the considerable mechanical advantage obtained by pressurizing a relatively incompressible dense liquid with a commercially available relatively small positive displacement reciprocating piston type liquid pumping system when compared to the large gas (air) compressors which would otherwise be required. Evaporation of the pressurized LN2 and heating of the driver gas can also be performed in a single pass with an in-line pebble-bed heater (i.e. through which the pressurized LN2 passes while pressurizing the drivers) rather than trying to use a bypass system.

An additional advantage of the LN_2 pebble-bed pressurizing and heating concept is that a LB/TS driver (pressure vessel) could be rapidly filled (in under 10 minutes) using a high capacity, off the shelf, positive displacement multiple cylinder cryopump in combination with a high flow/high heating rate pebble-bed evaporator/superheater. Rapid filling of the driver would greatly decrease the complexity of the driver system by eliminating the need for thermally insulating the interior walls of the driver to prevent large heat losses associated with a bypass systems's slow heating time (typically in the order of 1-2 hours). Because hazardous conditions exist in the test section when the LB/TS drivers are pressurized with ambient or elevated temperature gas, rapid filling and heating would allow LB/TS experimenters to correct any instrumentation or experiment problems in the test section up to 10 minutes prior to test without venting the drivers.

BRL is presently developing a 1/6th scale model of the LB/TS to produce a working test bed for LB/TS component technologies. The test bed utilizes an existing 2.44 meter (8 ft) diameter shock tube which is approximately 1/6th of the equivalent diameter of the full scale LB/TS test section (163 m^2 cross section hemicircle, D_{eqv} = 14.4 m). SPARTA has recently completed a BRL sponsored program[3] which resulted in the development, test and delivery of a fully qualified 1/48th scale LN_2 Pebble-bed Evaporator/Superheater. The test data from experiments with the 1/48th scale unit were used to generate the heat transfer performance parameters which SPARTA used in this program to design a LN2 pebble-bed evaporator/superheater for the BRL 1/6th scale LB/TS testbed (modified BRL 8 foot shocktube). These data are also applicable to the design of the LN2 Pebble-bed Evaporator/Superheaters for the full scale LB/TS.

3. OBJECTIVE

The primary objective of the Phase I Program was to make a detailed mechanical, thermal and structural design of a pebble-bed evaporator/superheater system that would produce pressurized hot nitrogen gas at a variable predetermined temperature from a cryogenic LN_2 source at pressures up to 2,200 psig at a LN_2 flow rate of 32 gpm (214.4 lbs/min). The flow rate is based on a 10 minute driver fill up time which is sufficient to fill the 1/6th scale BRL LB/TS driver rapidly enough and attain the required nitrogen temperatures with an uninsulated driver. The second objective of this program was to design an instrumentation and control system for the 1/6th scale model LN_2 pebble-bed evaporator/superheater that will be developed, tested and delivered to BRL.

4. DESIGN REQUIREMENTS

4.1 LB/TS Driver Design Conditions

The LB/TS driver conditions were calculated by BRL using a quasi one-dimensional shock tube simulation computer program, BRL-Q1D. The program calculates the shock properties for a given shocktube driver and driven section geometry. Driver data were provided to SPARTA by BRL.

The following Table 4-1 shows the driver gas design data provided to SPARTA by BRL in the contract work statement. In this set of data, seven LB/TS design points are shown. An additional case, 1A, was added to reflect recent BRL calculations indicating that pressures as high as 2200 psig may be required. It was assumed that the gas temperature remained the same as case 1 (i.e. 644°K). The maximum driver conditions (i.e. pressure and temperature) used in the design is case 1A; 15,168 kPa @ 644°K.

TAB'_E 4-1 1/6TH SCALE DRIVER DESIGN CONDITIONS

CASE	SHOCK OVERPRESSURE		DRIVER PRESSURE		DRIVER TEMPERATURE	
	psig	kPa	psia	kPa	°R	°K
1	35	241.3	1734	11956	1159	644
1A	35	241.3	2200	15168	1159	644
2	30	206.9	1506	10386	1042	579
3	25	172.4	1170	8069	947	526
4	20	137.9	1017	7010	857	476
5	15	103.4	785	5410	763	424
6	10	69.0	595	4104	637	354
7	2	13.8	103	710	518	288

The 1/6th scale driver geometry was also supplied by BRL and is as follows:

Driver Inside Diameter -	0.9144 meters (36 inches)
Driver Nominal Wall Thickness	5.715 cm (2.25 inches)
Driver Wall Material -	SA 516 Grade 70 Carbon Steel
Driver Nominal Length -	8.667 meters (28.5 feet)
Driver Volume -	5.69 m^3 (201 ft^3)

Note: The driver in this configuration is assumed to be insulated on the exterior of the vessel with near zero heat loss to the atmosphere.

4.2 Pebble-bed Heater Design Conditions

Table 4-2 gives the driver gas mass, LN2 volume, gas evaporation heat and superheat for each oi the cases shown in Table 4-1. These values are based on the following thermophysical properties of pure liquid/gaseous nitrogen:

Latent Heat of Vaporization -	85.6 Btu/lbm (199 kJ/kg)
Specific Heat @ Constant Pressure -	0.248 Btu/lbm/°R (1.038 kJ/kg/°K)
Boiling Temperature -	139°R (77°K)
Perfect Gas Law Constant -	0.0709 Btu/lbm/°R (23 kJ/kg/°K)

The gas mass/liquid volume shown in the table is based on a 1/6th scale driver volume of 5.69 m^3 (201 ft^3).

TABLE 4-2 1/6TH SCALE DRIVER GAS HEATING REQUIREMENTS

CASE	NITROGEN GAS/LIQ USAGE			EVAPORATION HEAT		SUPERHEAT		TOTAL HEAT EVAP & SUPER	
	lbm	kg	gal	MJ	kBtu	MJ	kBtu	MJ	kBtu
1	784	356	116	7.093	6.723	209.6	198.6	216.7	205.4
1A	994	452	147	8.999	8.529	265.9	252.0	274.9	260.6
2	757	344	112	6.853	6.496	179.3	169.9	186.1	176.4
3	648	294	96	5.861	5.555	137.1	130.0	143.0	135.5
4	622	283	92	5.626	5.333	117.0	110.9	122.6	116.2
5	539	245	80	4.875	4.620	88.1	83.5	93.0	88.1
6	489	222	72	4.429	4.198	63.9	60.6	68.3	64.8
7	104	47	15	0.942	0.893	10.3	9.8	11.3	10.7

Additional allowances for gas heat are required for the following heat loss and system operation conditions:

1. Heat loss to the transfer piping;
2. Heat loss to the driver wall;
3. Driver bleed off gas for pressure & temperature control;
4. Gas overheat (heated above required driver temperature) to compensate for temperature drops due to piping heat losses;
5. Increased gas volume from the pebble-bed and transfer piping; and
6. Possible shot holding periods (assumed < 2 times the fill time).

All these factors will increase the required heat output capability of the pebble-bed gas heating system.

4.2.1 Heatup Time Design Condition

The thermal design conditions of the pebble-bed heater are derived from the driver heating requirements as outlined above in Table 4-2. The LN_2 pumping system capacity determines the fill time for the driver. For a single pass pebble-bed heater, the cryogenic LN_2 pump capacity determines both the driver pressurization time and the driver heatup time. An "off the shelf" commercial LN_2 pumping system rated at 32 GPM was specified for use in pumping up the 1/6th scale test bed driver. This would enable the driver to be filled in the order of 5-10 minutes allowing for controlled driver bleed off and heat loss.

The specifications of this pump system are given in the following Table 4-3.

TABLE 4-3 PROPOSED 1/6TH SCALE LN2 CRYOGENIC PUMPING SYSTEM

32 GPM Liquid Nitrogen Cryogenic Pressure Pump
Manufacturer: Cosmodyne Corp., Torrance, CA
Model No. 3-GUPD Series (3 cylinder x 2.0" Bore x 1.3" Stroke
Maximum pressure capability: 3000 psig
Electric motor driven: 75 HP
Skid mounted with lube system and pump controls.

In addition to the LN_2 pump system outlined above, a supply of liquid nitrogen must be made available. A permanent storage tank of approximately 5000 gallons would be sufficient to supply LN_2 for approximately 25 high level (case 1A) tests. The LN_2 requirements are not only governed by the driver gas requirements as outlined above, but also by pumping system cooldown and supply tank pressurization which can use significant amounts of LN_2. A mobile LN_2 tanker truck can be used instead of a storage tank. Typical tanker capacities are 3000-5000 gallons. The advantage to a tanker is that LN_2 evaporation losses can be minimized by eliminating the transfer process from a tanker to a permanent storage tank. A small permanent tank (500-1000 gallons) is recommended for recovery of LN_2 bleed off while the pumping system is operating and heating is not desired (i.e. LN_2 is bypassed from the pebble-bed heater to a recovery tank).

The critical heatup time is dominated by the convective heat losses from the hot driver gas to the driver wall (insulated or uninsulated). To reduce excessive driver gas heat loss to the driver wall and surrounding atmosphere, the driver filling time should be short (in the order of 5 to 10 minutes) and the driver firing time delay (hold time after pressurization is complete) should be minimized. For safety and operational reasons, it is envisioned that the driver will be pressurized and fired only after all test articles, experiments and instrumentation in the test section have been checked out and verified. A calculation was performed to predict the convective heat loss to the wall of a cold, uninsulated driver and the results are outlined below.

4.2.2 1/6th Scale Driver Wall Heat Loss Calculations

Heat transfer rate to the driver walls is a maximum when the differential temperature between the gas and wall is the greatest. The mechanism for heat transfer within the driver is free convection within a closed horizontal cylinder. The ratio of enthalpy of the pressurized hot driver gas to the heat capacity of the steel driver, R_{gs}, is computed from the following equation:

$$R_{gs} = \frac{m_s \cdot Cp_s}{m_g \cdot Cp_g} \qquad \text{(EQ 4-1)}$$

where,

m_s, mass per unit length of the steel driver, kg/m
Cp_s, specific heat of the steel driver material, J/(kg·°K)
m_g, mass per unit length of the high pressure hot gas, kg/m
Cp_g, specific heat of the hot gas, J/(kg·°K)

The mass per unit length of the carbon steel driver (for d ≈ 1.0 m & t ≈ .057 m) is approximately 1396 kg/m and for the gas (Tg_o = 700°K & P_g = 12 MPa gives a density, ρ_g = 58 kg/m^3) is approximately 45.5 kg/m. For Cp_s = 450 J(kg·°K) and Cp_g = 1097 J(kg·°K), the enthalpy ratio, R, is approximately 13.

This result shows that the heat capacity of the steel driver is one order of magnitude greater than that of the driver gas. This implies that the driver wall does not appreciably rise in temperature over short periods of time and can be assumed to be at ambient temperature, T_o, throughout the short time pressurization of the driver.

The heat loss from the driver gas to the driver vessel can be calculated using the classical exponential temperature decay formula:

$$\frac{q}{L} = h \cdot \pi \cdot D \cdot (T_g - T_o) = \frac{d}{dt}\left[\rho_g \cdot \pi \cdot D^2/4 \cdot Cp_g \cdot (T_g - T_o)\right] \qquad \text{(EQ 4-2)}$$

Integrating & Solving for T_g-T_o:

$$\frac{T_g - T_o}{T_{go} - T_o} = e^{(-t/\tau)} \qquad \text{(EQ 4-3)}$$

where;

T_g, temperature of the gas at time t, °K
T_{go}, initial temperature of the gas, °K
T_o, initial and constant temperature of the steel driver, °K
t, time, sec

τ, time constant $= \dfrac{\rho_g \cdot D \cdot Cp_g}{4 \cdot h}$, sec (EQ 4-4)

ρ_g, gas density, kg/m^3

h, the convective heat transfer coefficient, $W/(m^2 \cdot {}^\circ K)$.

The convective film coefficient is calculated from the following correlation [4]:

$$Nu_D = \frac{h \cdot D}{k_g} = 0.40 \cdot (Gr_D \cdot Pr)^{0.20} \qquad \text{(EQ 4-5)}$$

Valid for $10^6 < Gr_D \cdot Pr < 10^8$

where,

Nu_D, Nusselt number
Gr_D, Grashof number

given by;

$$Gr_D = \frac{g \cdot \beta \cdot (T_o - T_{go})^{0.5}}{(\mu/\rho_g)^2} \approx 2 \cdot 10^{13} \qquad \text{(EQ 4-6)}$$

g, gravitational constant
ß, volume coefficient of expansion ≈ $1/T_{go}$
μ, dynamic viscosity of gas @ T_g, kg/m/s
Pr, Prandtl number ≈ .7
k_g, thermal conductivity of gas ≈ 0.04 W/m/°K
D, driver internal diameter = 1.0 m

therefore: $h \approx 7.0\ W/m^2/{}^\circ K$

The time constant is calculated as:

$\tau \approx 2270$ sec (38 minutes)

This implies that the gas temperature will be reduced by e^{-1} (≈37%) in 38 minutes.

For a wall temperature of 290°K, in 5 minutes the gas temperature will drop from 700°K to approximately 649°K (8% reduction). In 10 minutes the gas temperature drops to approximately 605°K (14% reduction).

Assuming that the above analysis is valid, the heating time for the approximately 1.0 m diameter driver (1/6th scale) can be as little as 5 minutes provided that a large enough flow capacity LN_2 cryogenic pump is used. High capacity cryogenic LN2 pumps are commercially available "off the shelf" items. For a larger 2.0 m diameter driver (full scale), the time constant increases, thus implying that a full scale uninsulated driver should be heated in 15 minutes or less, provided that sufficient LN_2 pumping capacity is made available. In general, because the exponential time constant, τ, and the heat transfer coefficient, h, are proportional to the inverse of the driver diameter, the larger the driver diameter, the longer the fill time can be. Although this analysis shows that fill times in the order of minutes can produce the required driver conditions without driver insulation, the heat transfer correlation (EQ 4-5) may not be valid for the range of the Grashof number calculated for the fill conditions. The calculated Grashof number is roughly 5 orders of magnitude greater than the correlation allows. Thus, without a valid heat transfer correlation, driver fill tests must be performed to obtain the necessary design data to predict the 1/6th and full scale driver gas heat loss to an uninsulated driver wall.

4.2.3 1/6th Scale Driver Heating Requirements

For the 1/6th scale LB/TS gas pressurization and heating system, the design requirements for pressure, temperature and pressurization/heating time are the same as the full scale LB/TS. However, the driver gas volume, driver vessel diameter, gas mass and total gas heat input vary directly with the decreased driver volume. When one compares the driver volumes of the 1/6th scale BRL facility with the driver volume of the LB/TS, the scale of the BRL 8 ft. shock tube test bed is approximately 1/5th of the full scale LB/TS.

When calculating the size of the pebble-bed heater, the required pressurized hot

gas volume must include the pebble-bed evaporator/superheater volume and the miscellaneous piping volume. This volume has been estimated to be approximately 5% of the driver volume. Other allowances are made for heat losses in the heater system and driver and for potential holding times which may require additional heated gas to keep the driver gas temperature at required levels.

Driver gas heat losses are accounted for by increasing the driver gas inlet temperature. A value of 50°K (90°R) was chosen because the results of the heat loss (gas to the driver wall) calculations indicated that the temperature of the driver gas will drop from 700°K to 649°K in 5 minutes.

If the temperature in the driver is initially too hot for the required simulation after pump up, the driver walls will cool the gas to the required temperature in a matter of minutes. Compensating for the pressure drops due to the decreased gas temperature can be performed by continually pumping more hot gas into the driver while simultaneously bleeding cooler gas out. When the required driver conditions are met, the driver diaphragm/valve will be initiated. Adequate temperature and pressure monitoring in the driver will ensure that the pressure and temperature conditions are satisfactory before initiating the diaphragm/valve. Detailed analyses will have to be performed on the influence of small driver pressure and temperature perturbations on the test section shock properties in order to properly design the accuracy of the controls.

Allowing for the miscellaneous piping and pebble-bed gas volume (assumed 5% of driver volume), the total heated gas volume is $5.7 \cdot 1.05 \approx 6.0$ m^3 (212 ft^3). The volume difference of 0.3 m^3 (10.6 ft^3) is roughly equivalent to the combined volume of a 2 ft diameter by 6 ft long pebble-bed, 6" thermal mixer chamber and 140 feet of 2.5" schedule 160 piping.

The gas mass at a volume of 6 m^3, a maximum pressure of 15.2 MPa and a gas temperature of 644°K + 50°K = 694°K (1249°R) is 444 kg (977 lbm). The heat input to the gas is 8.84 MJ (8.37 kBtu) for vaporization (i.e. phase change to boiling temperature)

and 284.4 MJ (269.5 kBtu) for superheat (rise from boiling temperature of 77°K to 694°K) for a total heat input of 293.2 MJ (277.9 kBTU). This amount of heat is approximately 35% more than the case 1A required driver gas heat enthalpy as given in Table 4-2. The requirements for the 1/6th scale LN_2 pebble-bed evaporator/superheater are summarized in Table 4-3.

TABLE 4-4 1/6TH SCALE LB/TS DRIVER PEBBLE-BED HEATER REQUIREMENTS

CASE	CONDITION	DESIGN REQUIREMENT
1	Maximum gas temperature:	644°K (1159°R)
1	Gas temperature overheat:	50°K (90°R)
1	Maximum gas pressure:	15.2 MPa (2200 psig)
1	Mass of heated gas:	444 kg (977 lbm)
1	Maximum heat into gas:	293.2 MJ (277.9 MBtu)
	Driver gas volume:	5.7 m^3 (201 kft^3)
	Misc gas volume:	0.3 m^3 (10.6 kft^3)
	Driver Gas Heating time:	5 minutes (300 secs)
	Flowrate (5 minute	fill time)
	Mass:	1.48 kg/s (3.25 lbm/s)
	Standard volumetric*:	75.9 skl/min (2681 SCFM)
	LN_2 volumetric:	109.3 l/min (28.8 GPM)

4.3 Mechanical Design Requirements

The mechanical design for the 1/6th scale pebble-bed evaporator/superheater is primarily driven by the American Society for Mechanical Engineers (ASME) code specifications for the safe operation of an elevated temperature high pressure vessel. The design specifications are taken primarily from the 1983 version of the ASME Boiler and Pressure Vessel Code. Other design requirements were developed from standard safe engineering practices.

The structural requirements for the pressure components of the pebble-bed evaporator/superheater were developed according to guidelines in the ASME Boiler and

* Standard Conditions: 293.1°K & 101.35 kPa (530°R & 14.7 psia)

Pressure Vessel Code. The following three conditions constitute the primary design parameters for pressure vessels:

(a) Design Working Temperature
(b) Design Working Pressure
(c) External Loadings

According to the ASME code, the design temperature is the maximum mean metal temperature expected during the most severe operation of the vessel. The metal surface temperature must never exceed the material's rated maximum temperature as given in the ASME code for the class of materials being used. The design pressure is the maximum pressure differential achieved across the inner and outer walls of the vessel.

There are two major pressure vessels in the pebble-bed design, the pebble-bed containment vessel and the thermal mixing chamber vessel. The ASME design working pressure and temperature for the two vessels are as follows:

Pebble-bed vessel: 2200 psig @ 500°F maximum mean metal temperature.
Mixer vessel: 2200 psig @ 850°F maximum mean metal temperature.

External loading requirements include the following factors:

(a) Weight of the vessel.
(b) Hydrostatic head of the fluid or mass in the vessel.
(c) External support structural loads.
(d) Thermal expansion/stress induced loads.
(e) Dynamic loading from environment or pressure surges.

The most important aspects of the ASME code requirements are:

1) The appropriate structural materials must be selected for the service environment,
2) The pressure vessel must be designed according to the rules outlined in the code,
3) The pressure vessel must be fabricated by qualified ASME Code rated manufacturers and
4) The pressure vessel must be hydrostatically pressure tested to a minimum of 1.5 times the working pressure times a factor to compensate for the hydrotest temperature and the operating temperature of the vessel.

Elevated temperature pressure vessels require hydrostatic proof tests at higher pressure than that specified if the pressure tests cannot be performed at the design working temperature. Radiographic inspections are required by the ASME on the welds of the pebble-bed pressure vessel if the wall thickness exceeds 1.50 inches as required.

All aspects of the ASME material and pressure vessel design requirements are to be followed for the pebble-bed evaporator/superheater components. Material certifications will be provided for all pressure vessel components and all welds will be inspected radiographically.

5. PEBBLE-BED THERMODYNAMIC MODELING AND PRELIMINARY DESIGN

The thermodynamic modeling and preliminary sizing of the pebble-bed for the 1/6th scale system was performed in the same manner as the 1/48th scale design (see reference 3). The only exception is that pebble-bed performance data taken from 1/48th scale tests was used to modify the pebble-bed thermal performance model that sized the 1/6th scale unit.

5.1 Pebble-bed Thermal Storage Mass Selection

The desirable characteristics for a thermal storage material include the following:

(1) High specific heat
(2) High thermal diffusivity
(3) High density
(4) Reversible heating and cooling
(5) Chemical and geometric stability
(6) High operation temperature
(7) Low cost
(8) Sufficient strength and elongation at high temperature to withstand packing compression.
(9) Resistance to thermal shock

Table 5-1 shows a material evaluation chart which ranks density, heat capacity, thermal conductance, temperature limit, cost, compressive strength and corrosion resistance for three material classes of interest.

TABLE 5-1 THERMAL STORAGE MATERIALS EVALUATION CHART

MAT. CLASS	TOTAL RANK	DENS	Cp	K	Tmax	COST	COMP STR	CORROSION RESISTANCE
		5%	20%	20%	20%	10%	10%	15%
NI-FE	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.0
NI	1.24	1.25	1.00	2.00	1.00	0.90	1.00	1.25
STEEL	0.95	1.00	1.00	0.75	0.90	2.00	0.90	0.5
ALUMINA	1.50	0.52	2.00	0.23	2.00	2.50	0.50	2.0

Each criterion is ranked relative to the nickel-iron class material (NI-FE) which has the value 1.00 for all 6 criterion. The Ni-Resist nickel-iron alloy was used for the 1/48th scale pebble-bed system manufactured under a previous program and is a proven material for this application.

Weighting factors are used to show the relative importance of each criterion in the total thermal storage system design. Heat capacity, thermal conductivity and temperature limit are weighted the highest at 20% followed by corrosion resistance at 15%, cost and strength at 10% and density at 5%. Total ranking values which are less than 1.0 show a decreased performance in the thermal storage application and greater increased performance over iron materials.

The highest ranking material, aluminum oxide ceramic (AL_2O_3), is readily available in standard ball forms of various sizes. Although it is a brittle material, it has been used in high temperature gas (as opposed to cryogenic) pebble-beds and has a thermal performance rank on par with nickel-iron. Ceramics, however, tend to fracture more easily, especially if high thermal stresses are imposed on the material. The hot ceramic balls (now operating at temperatures up to 2000°F) may fracture and produce ceramic dust when exposed to the cryogenic LN_2 spray. The ceramic dust could seriously damage valve seals and other components as well as degrade the performance of the heater over extended use. Without tests to prove ceramics applicability to the pebble-bed system, the design cannot be made as reliable as the 1/48th scale system.

Pure nickel is a possible alternative to the nickel-iron alloy or ceramic. Fabrication costs for the 0.75" balls used in the previous program dominated the cost of the material. Pure nickel is available from International Nickel Company (INCO) in rough ball sizes up 3/8" diameter. This form of the material is a high purity grade nickel generally used for alloying for aircraft quality materials or in nickel plating applications. Because of vast nickel price fluctuations in the last few years, it is not certain at this time if the use of this form of nickel is economically competitive. As of the date of this report, nickel is a good candidate and can be economically competitive with the other materials.

An alternative design could utilize both materials within the bed. At the entrance to the bed, where LN_2 is sprayed directly onto the heated pebble-bed surface, the pure nickel or nickel-iron balls can be used. Further down the bed where only gaseous nitrogen flows, ceramic balls could be used with high confidence in their reliability.

At the time of the development of the prototype 1/48th scale pebble-bed system, ceramic and Ni-Resist materials had the same relative cost per pound. A price increase has occurred in the last few years where nickel prices have almost tripled. As a result, Ni-Resist has become more expensive to produce for this pebble-bed application. However, it is a proven material and is still considered superior to all other materials. Tests on nickel plated carbon steel and alumina balls are being proposed which may prove that these materials are as reliable as Ni-Resist under repeated thermal shock cycles. The properties of Ni-Resist nickel-iron and alumina are given below.

	Ni-Resist	Alumina
Density (kg/m^3):	6960	3600
Specific Heat (J/(kg·°C):	450	920
Conductivity (W/(m·°C) @ 400°C:	20	7
Maximum use temperature (°C):	870	1500

5.1.1 Pebble-bed Materials Cost Analysis

Significant pebble-bed material cost savings can be realized if aluminum oxide can be validated for use in the extreme pebble-bed thermal shock environment and substituted for the currently used Ni-Resist alloy balls. The specific heat capacity per unit volume for alumina is 3.312 $MJ/m^3/°K$ and for Ni-Resist is 3.132 $MJ/m^3/°K$. Alumina, therefore, has approximately 6% more heat capacity than Ni-Resist for an equal volume of material. Based on a 3/4" diameter ball shape, the October 1988 price for alumina is $1.50/lb ($3.30/kg) and for Ni-Resist is $5.50/lb ($12.10/kg). The cost per unit volume for alumina is $11,880/$m^3$ ($0.20/$in^3$) and for Ni-Resist is $84,216/$m^3$ ($1.38/$in^3$). Therefore, based on a equal volume of pebble-bed material, the cost of alumina is approximately 15% of the cost of Ni-Resist. The cost savings for substituting alumina in the 1/6th scale pebble-bed currently designed for 5500 lbs of Ni-Resist pebble-bed material is (1 - .15)·$30,250 = $25,713. For the full scale pebble-bed systems that use approximately 270,000 lb (9 pebble-beds @ 30,000 lbs of pebbles/bed) of Ni-Resist material at a cost of $1,485,000, **the cost savings is $1,262,250**. Therefore, the cost of the pebble-bed material for the 9 full scale driver gas heating systems is reduced to only $222,750.

5.2 Pebble-bed Thermodynamic Modeling

Under the previous program (see Reference 3), a 1/48th scale pebble-bed combined LN_2 evaporator and superheater system was developed and fabricated. Tests were performed and time dependent temperature data were collected for LN_2 flowrates up to 8 GPM and static back pressure up to 1800 psig. These test data were then correlated with a pebble-bed thermal performance model previously developed and a correlation factor was added to the model to provide a tool for design of the 1/6th and future full scale pebble-bed units.

A standard heat transfer correlation for a packed bed of spheres was found which provided a basis by which the above model could be used. The relation is for single

phase flow through a bed of packed spheres. This correlation is used in the pebble-bed model to calculate a heat transfer coefficient which is then used to calculate the temperature profile of the bed and gas over time. A simple proportional constant was added to the relation to correlate the available test data. The heat transfer correlation[5] is given in the following equation.

For turbulent flow $St_D \cdot Pr^{2/3} = .687 \cdot Re^{0.327}$ $120 < Re < 2000$ (EQ 5-1)

where,

St_d, Stanton Number based on pebble diameter, $= \dfrac{Nu_d}{Re_d \cdot Pr}$ (EQ 5-2)

Nu_d, Nusselt Number based on pebble diameter $= \dfrac{h \cdot d}{k_f}$ (EQ 5-3)

Pr, Prandtl Number

Re_d, Reynolds Number based on pebble diameter $= \dfrac{\dot{m}d}{S_f r \cdot \mu_f}$ (EQ 5-4)

$\dot{m}$, Mass flowrate of fluid/gas, kg/s
h, Heat transfer coefficient, $W/m^2/°K$
d, Diameter of the individual spheres, m
μ_f, Dynamic viscosity of the gas, kg/(m·s)
k_f, Thermal conductivity of fluid/gas, W/(m·°K)

The properties of the fluid/gas for this empirical relation are evaluated at a reference temperature, T_{ref}, given by:

$$T_{ref} = T_\infty + 0.5 \cdot (T_w - T_\infty) \quad \text{(EQ 5-5)}$$

T_∞, Average free stream fluid/gas velocity, °K
T_w, Wall temperature of spheres, °K

Solving for h and adding a multiplier correlation constant C,

$$h = C \cdot \frac{k_f}{d} \cdot 0.687 \cdot Pr^{1/3} \cdot Re^{.673} \quad \text{(EQ 5-6)}$$

An example calculation of the heat transfer coefficient for nitrogen gas at cryogenic temperature exposed to a hot bed (1/6th scale configuration) is given below for the flowrates; 32 GPM LN_2. The sphere diameter, d, is given as 0.75" (0.019 m), the bed cross-sectional frontal area, Sfr, is given as 3.41 ft^2 (0.317 m^2) based on a 25 inch (0.635 m) diameter bed, the bed length, L, is 70" (1.78 m), and the heat transfer surface area, As, is ≈ 1241 ft_2 (115 m_2).

Assume; Tw = 1260°K (2268°R) and T_∞ = 90°K (162°R)

Evaluating reference temperature, $T_{ref} \approx 675$°K (1215°R)

Properties of nitrogen at T_{ref}; $\mu_f = 31.4 \cdot 10^{-6}$ kg/(m·s)

$k_f = 0.0498$ W/(m·°K)

$Pr = 0.690$

For 32 GPM (3.6 lb/s;1.6 kg/s); $Re_d = 3130$

and

$h = C \cdot 358$ W/(m^2·°K)

The calculated Reynolds number is greater than the maximum valid number for the correlation (i.e. 2000) and is corrected by using the correlation constant, C, calculated from the 1/48th scale test data. The correlation factor as developed from previous scaled test data was shown to be 0.85 from reference 3. The nominal heat transfer coefficient calculated above thus becomes; h = 304 W/(m^2·°K).

Pebble-bed sizing calculations were performed using the program "PEBBED" and a modified heat transfer coefficient. Figures 5-1 through 5-5 show the maximum integrated heat and heating rate output versus flow time for a Ni-Resist bed diameter of 0.635 m (2.08 ft) and bed lengths of 1.0, 1.25, 1.5, 1.75 and 2.0 meters, respectively. The thermal model does not directly account for phase change heat transfer and assumes constant flow through the bed (i.e. no bypass). Phase change, however, is indirectly accounted for through the use of the correlation factor developed from 1/48th scale

tests.

The constant flow thermal performance model can be related to the actual system which bypasses pebble-bed flow to a thermal mixing chamber by examining the total heat transferred to the gas. In either case, constant flow or bypassed flow, the same heat enthalpy must be transferred to the gas over an equal flow time period. The output gas temperatures, however, are much different. The constant flow case produces very high temperature gas (initially approaching the pebble-bed initial temperature) without control and the bypass flow produces a highly controllable outlet temperature gas. The thermal model results given here will be discussed in more detail in Section 5.3.

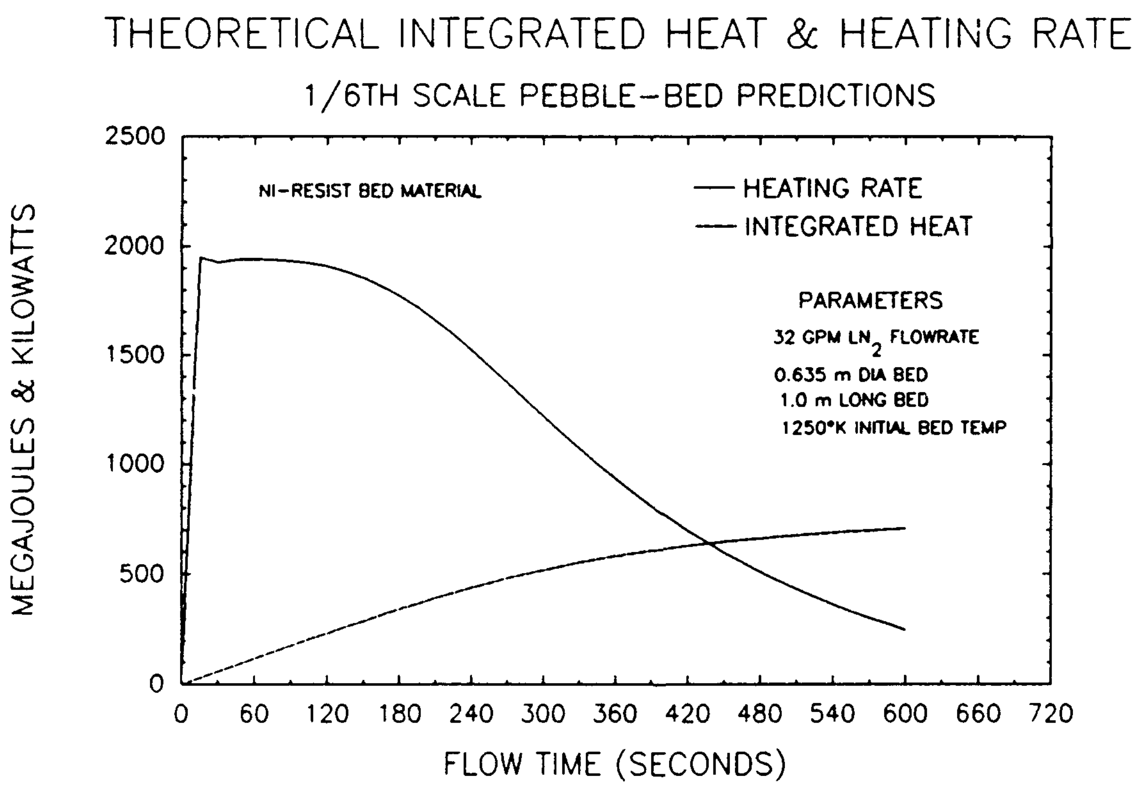

FIGURE 5-1 THEORETICAL PEBBLE-BED CALCULATIONS FOR 1/6TH SCALE CONFIGURATION - 1.00 METER BED LENGTH.

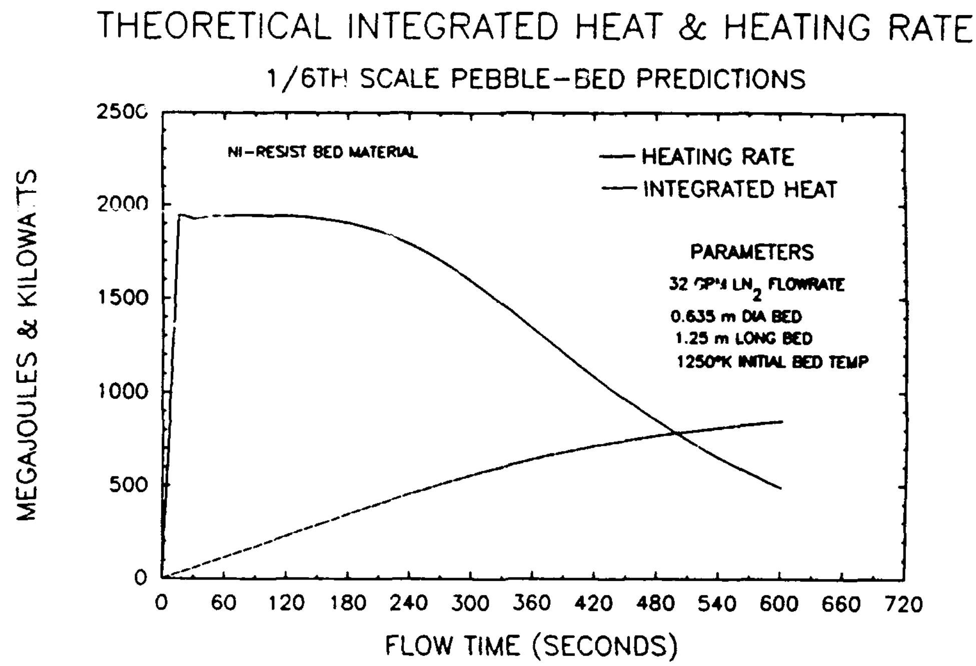

FIGURE 5-2 THEORETICAL PEBBLE-BED CALCULATIONS FOR 1/6TH SCALE CONFIGURATION - 1.25 METER BED LENGTH.

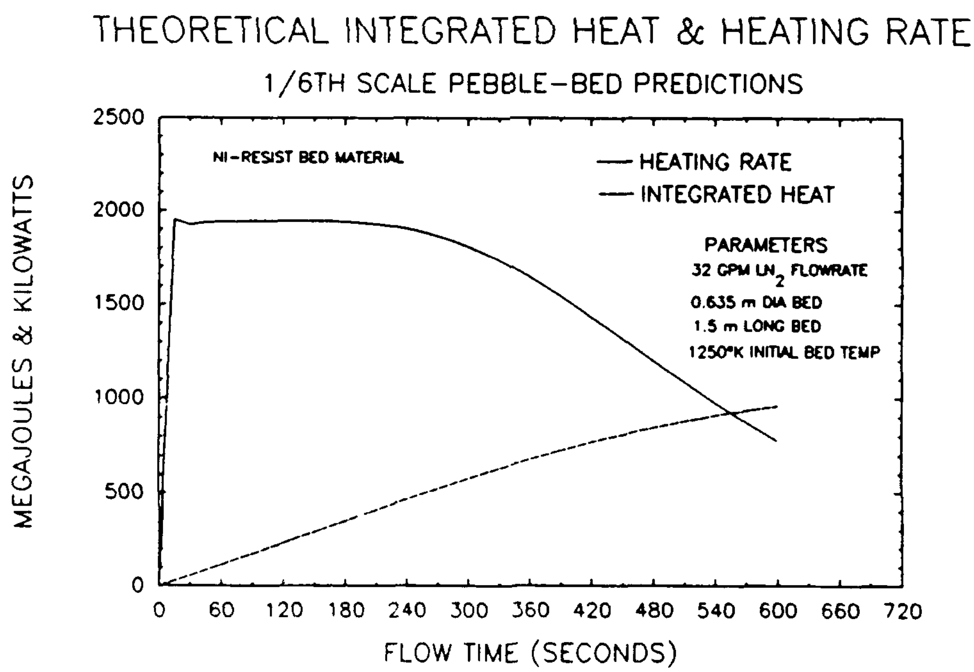

FIGURE 5-3 THEORETICAL PEBBLE-BED CALCULATIONS FOR 1/6TH SCALE CONFIGURATION - 1.50 METER BED LENGTH.

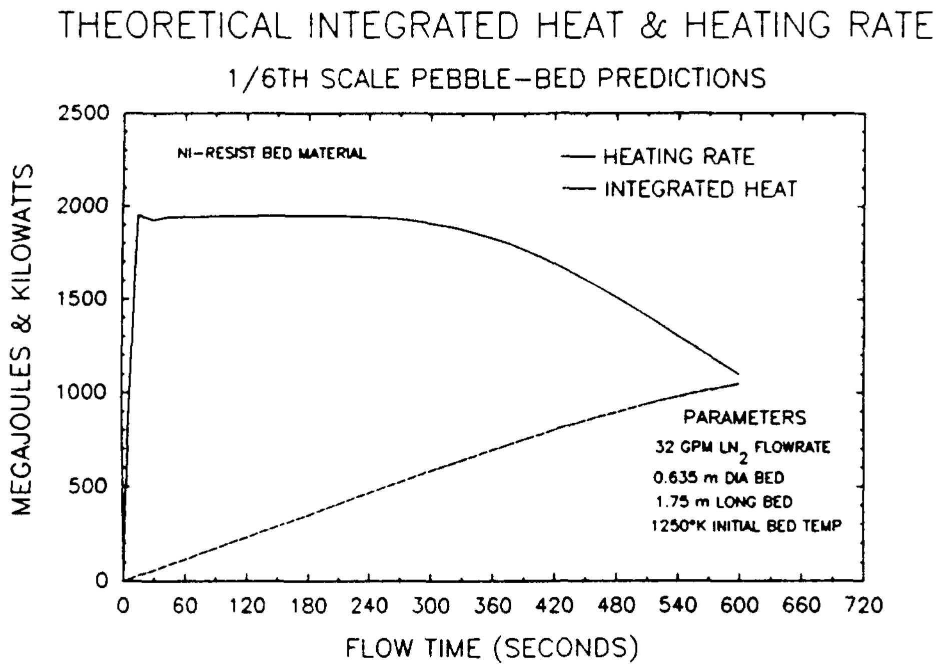

FIGURE 5-4 THEORETICAL PEBBLE-BED CALCULATIONS FOR 1/6TH SCALE CONFIGURATION - 1.75 METER BED LENGTH.

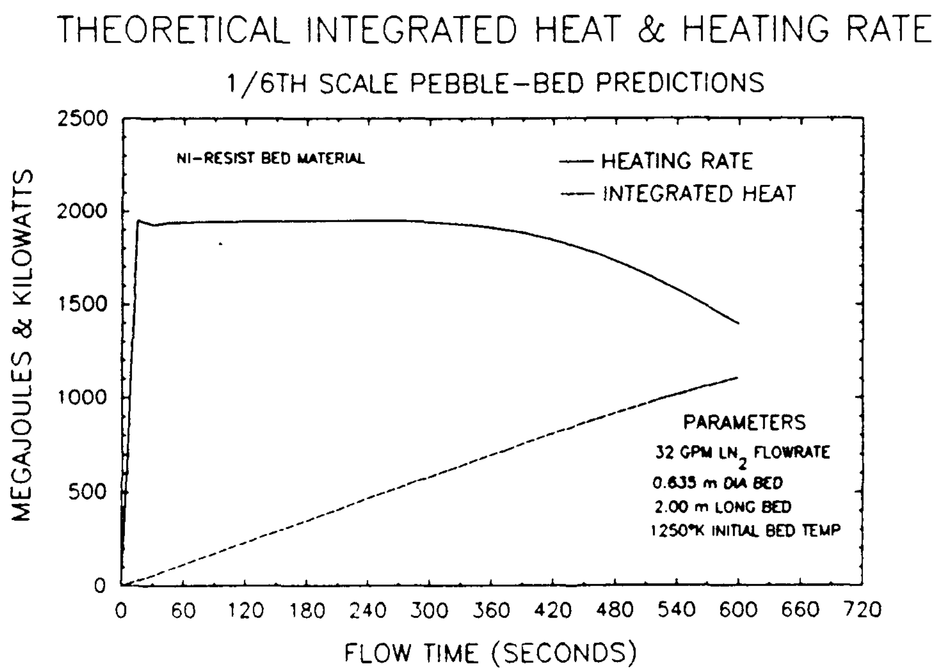

FIGURE 5-5 THEORETICAL PEBBLE-BED CALCULATIONS FOR 1/6TH SCALE CONFIGURATION - 2.00 METER BED LENGTH.

5.3 1/6th Scale Pebble-Bed Sizing

The 1/6th scale pebble-bed evaporator/superheater for the BRL 2.44 meter shock-tube testbed is sized according to the theoretical calculations. A simplified heat analysis was performed to estimate total heat capacity of the sized pebble-bed and to validate theoretical predictions. Heat capacity of the pebble-bed can be increased in a number of ways, the most economical being an increase in the pebble-bed initial temperature.

At the time of the design of the previous 1/48th scale pebble-bed unit, heater elements were limited to a maximum temperature of 1500°F. Upon closer investigation under this program, heater elements were located which can be used at temperatures as high as 2000°F. By temperature increase alone, the bed capacity can be increased by 67% assuming an identically sized bed. The problems associated with higher temperatures are increased insulation thickness, longer heating times and higher gas outlet temperatures (the latter results in more bypassed LN_2). All calculations assume nickel iron (Ni-Resist) alloy as the bed material at an initial bed temperature of 1250°K (1800°F).

Under the previous study, design constraints were imposed by components and design criteria. The primary constraining factor of pebble-bed size is the length of the pebble-bed because the electric heater elements that are used to thermally charge the system are length limited. Heater elements become difficult and expensive to manufacture if the length extends beyond 120 inches. Additionally, the bed is mounted in the vertical position to facilitate pebble packing and minimize gas flow channels that may result with a horizontal bed. Thus, because of the extensive instrumentation, piping and valving that must be installed at the bed entrance (top), a height limitation of 15 feet for the entire pebble-bed assembly was imposed to ease access to upper components.

With the height constraint controlled by heater element length and access limitations, the 1/6th scale pebble-bed assembly height is approximately that of the 1/48th scale unit previously developed. To increase capacity, the diameter of the bed is increased. As a starting point, the bed diameter was doubled (from 1/48th scale) which

provides roughly 4 times as much capacity (volume). This is consistent with test results from the previous study where the 1/48th scale pebble-bed produced approximately 110 MJ of energy during a 8 GPM test for 5 minutes where a total of 140 kg (308 lb) of LN_2 was vaporized and heated to 700°F (644°K). The bed diameter used for sizing is 25.0" (0.635 m) which is approximately twice the bed diameter of the 1/48th scale unit. Assuming an identical length as the 1/48th scale unit, the volume as roughly increased by a factor of 4 by doubling the diameter.

The calculations performed and summarized in the above figures indicate a much higher heat capability than simply 4 times the 1/48th scale configuration. This is primarily because the bed temperature increased from 1400°F to 1800°F. The heat capacity of a 1.75 m long 1/6th scale pebble-bed is roughly 600 MJ of heat transferred to the gas in 5 minutes time. This is roughly 2 times that required by the driver per Table 4-2 Case 1A. A final bed length of 1.75 meters was chosen because it allows ample hold capacity and can provide additional capacity should it be needed. Most importantly, however, is that new types of heater elements are being tried with this bed and if bed temperatures of 1800°F to 2000°F cannot be satisfactorily achieved in the 1/6th scale unit, then ample capacity to operate at 1400°F is available.

6. 1/6TH SCALE PEBBLE-BED DETAILED MECHANICAL DESIGN

ASME Pressure Vessel Code

The pebble-bed heater mechanical design was made according to the rules and practices of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code to provide a safe and reliable system. Section VIII, Division 1 of the ASME code provides basic requirements for the design methodology and fabrication of pressure vessels which operate at pressures up to 3000 psig and at temperatures to the maximum ASME specified temperature rating for the material for all nonnuclear rated pressure containment vessels. Section VIII, Division 2 provides alternate rules for pressure vessel design and allows for higher pressure vessels (>3000 psig) that require a more thorough

and precise design methodology. Division 2 rules and practices are meant for use on specially constructed pressure vessels for high pressure.

The following equations specify minimum pressure vessel wall thickness and maximum pressure for ASME vessels. The first equation calculates the thickness of a pressure shell based on the maximum circumferential (hoop) stress:

$$t = \frac{P \cdot R}{S \cdot E - 0.6 \cdot P} \quad \text{or} \quad P = \frac{S \cdot E \cdot t}{R + 0.6 \cdot t} \qquad \text{(EQ 6-1)}$$

The second equation calculates the thickness of the shell based on the maximum longitudinal stress:

$$t = \frac{P \cdot R}{2 \cdot S \cdot E + 0.4 \cdot P} \quad \text{or} \quad P = \frac{2 \cdot S \cdot E \cdot t}{R - 0.4 \cdot t} \qquad \text{(EQ 6-2)}$$

where,

P, design working pressure, psig
R, internal radius of the shell, in
S, maximum allowable tensile stress at the design working temperature, psi
E, weld joint efficiency

These equations were used to specify all pertinent wall thicknesses using a weld joint efficiency of 0.9.

ASME Material Specifications and Selection

The ASME material specifications were examined to determine what materials are required and applicable for the various components of the pebble bed heater design. The examination of Code materials indicate the use of the following materials in the respective application.

Pebble Bed Pressure Vessel and Misc Piping (ASME specification SA-XXX):

SA-105 Forgings, Carbon Steel, for Piping Components

SA-106 Seamless Carbon Steel Pipe for High Temperature Service

SA-182 Forged or Rolled Alloy-Steel Pipe, Flanges, Forged Fittings, and Valves and Parts for High Temperature Service

SA-312 Seamless and Welded Austenitic Stainless Steel Pipe for High Temperature and General Corrosive Service

SA-403 Wrought Austenitic Stainless Steel Fittings

6.1 Pebble-bed Heater System Components

There are 3 main assemblies of the pebble bed heater assembly. These are:

(1) Heater Bed Pressure Shell & Heads, Carbon Steel.
(2) Thermal Mixer Pressure Shell, Stainless Steel.
(3) Pebble-Bed Liner, Stainless Steel.

The mechanical design for the heater bed pressure shell is shown in Figure 6-1. The thermal mixer pressure shell design is shown in Figure 6-2.

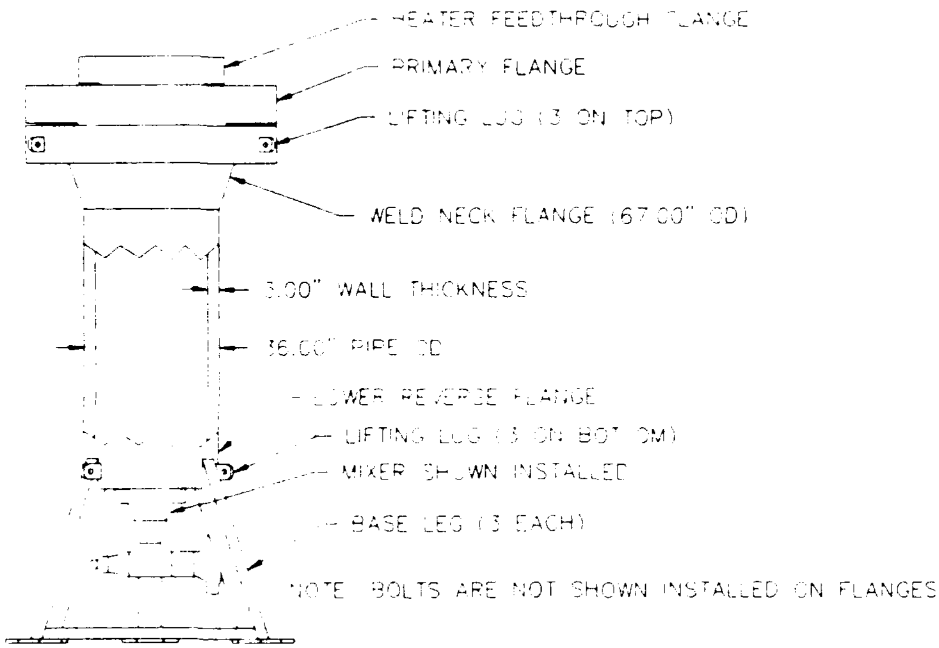

FIGURE 6-1 PEBBLE-BED HEATER SHELL CONCEPTUAL DESIGN.

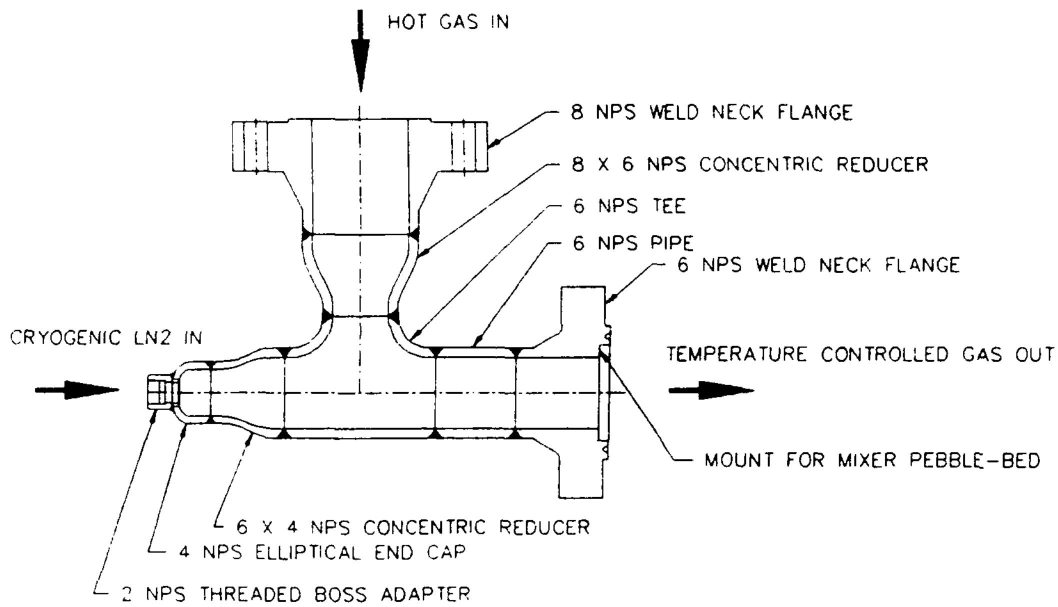

FIGURE 6-2 THERMAL MIXING CHAMBER CONCEPTUAL DESIGN.

6.1.1 Heater Pressure Containment Shells

The heater pressure shell is composed of pressure parts rated according to ASME pressure vessel code standards. The pebble-bed pressure shell is fabricated from SA-105 carbon steel forgings. Three forged parts are butt welded together to form the containment vessel:

(1) Weld Neck Flange (67" OD x 10" thick)
(2) Seamless Pipe (36" OD x 30" ID)
(3) Reverse Weld Neck Flange (36" OD x 8" thick)

Like the 1/48th scale design, the pressure shell has three legs integrally welded to the vessel structure. Struts connect the legs at the base and add considerable stability to the base support structure.

The upper header assembly is composed of two flanges. The large 67" OD x 10" thick header flange bolts to the weld neck flange using 32 2.75" diameter bolts. A second

smaller flange is then bolted to the 67" OD flange. This flange is a standard ANSI 20 NPS 1500 LB blind flange. It is through this flange that the heater elements and instrumentation are fed through to the pebble-bed.

6.1.2 Cryogenic LN_2 Components

The components used for cryogenic fluid transport at high pressure are required to be made from stainless steel to prevent embrittlement common with carbon steel material that is or may be subjected to cryogenic temperatures. All components which are subject to be exposed to LN_2 are constructed of type 304 or type 316 stainless steel. Both of these grades are approved by ASME for use at cryogenic temperatures.

6.1.3 Pebble-bed Design

Heater Bed Liner

The heater bed liner and baffle assembly is shown in Figure 6-3 with the pebbles shown in the upper section only. 36 electric heater elements are inserted axially into the two concentric circular arrays of tubes shown in the figure. There are a total of 6 equally spaced baffle plates which aid in the uniform distribution of the gas as it flows through the heater and prevents channeling of the flow through regions or channels with lower flow resistance.

The upper baffle plate houses 28 spray nozzles and the LN_2 distribution manifold to distribute a spray of LN_2 over the top surface of the bed. This plate is sealed from the above insulated surface so that LN_2 does not inadvertently impinge on any carbon steel surface and degrade material properties. Three different sizes of nozzles are used in the design based on the maximum flowrate of 32 GPM. The bulk of the LN_2 flow (≈ 20 GPM) will be distributed using 12 each of a 1.68 GPM @ 40 psi backpressure 120° spray angle nozzle. These nozzles distribute flow from the bed center out to approximately 16.0" in diameter (8 nozzles on a 14.0" diameter circle and 4 on a 6.0" diameter circle. The remaining flow (≈ 12 GPM) is distributed using 16 each of a 0.75 GPM @ 40 psi

backpressure 90° spray nozzle. These nozzles distribute flow from a diameter of 16.0" out to the bed outer diameter (16 nozzles on a 21.0" diameter circle.

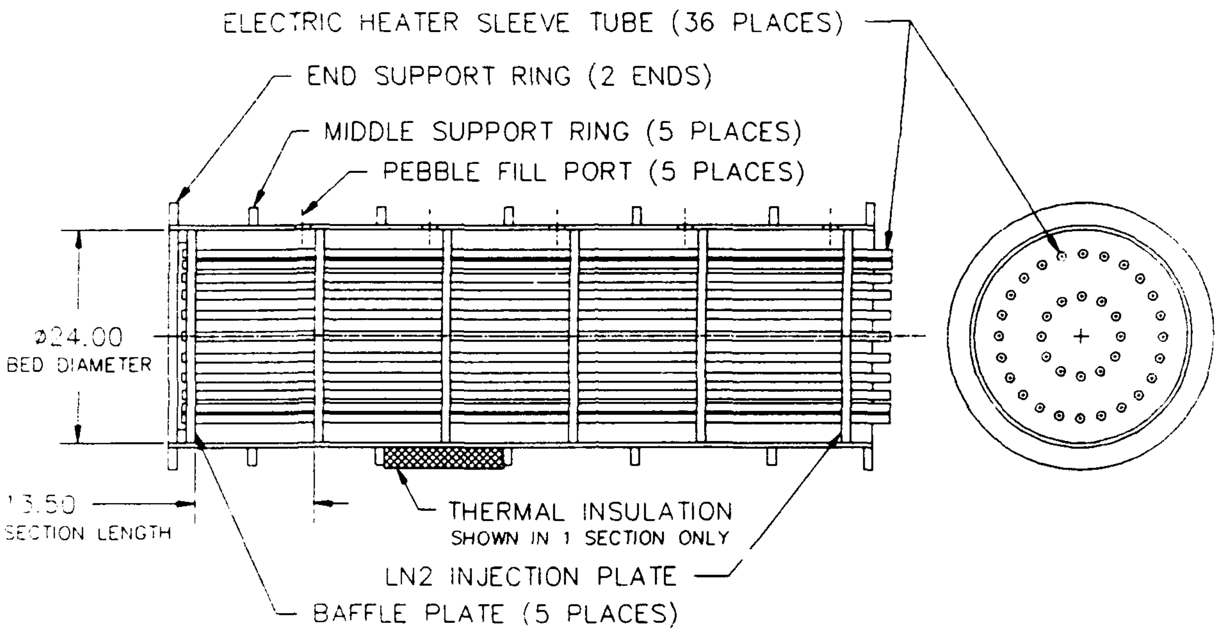

FIGURE 6-3 PEBBLE-BED HEATER LINER AND BAFFLE CONCEPTUAL DESIGN.

6.2 Pebble-Bed Heat Losses and Insulation Design

Several factors contribute to the heat loss and the resulting inefficiency of the pebble-bed heater system. The primary heat loss is from the hot bed through the pressure containment vessel and to the atmosphere during the charging (heat up) cycle. To minimize this heat loss and at the same time reduce the wall thickness requirements foi the outer pressure containment vessel, the pebble-bed is insulated from the outer pressure vessel wall using a ceramic blanket type insulation commonly used in furnaces and heat exchangers. Without such insulation, the heavy pressure vessel wall would rapidly reach temperatures in the order of the bed temperature and therefore require expensive high temperature stainless steel alloy or superalloy materials.

Secondary heat losses result from fill piping and valving losses while pressurization of the driver is being performed. These losses can be minimized in two ways: preheating the piping/valving to an intermediate or operational temperature and by insulating the piping/valving on the interior/exterior. While exterior insulation is commonly found and used in industry, interior insulation is much more difficult to install and maintain and may not be practical in view of the rapid system pressure drops.

The design goal is to develop an efficiently operating, safe pebble-bed heater. Efficient means maximum transfer of thermal energy from the pebble-bed heating system to the driver gas. Safe means operation of a pressure vessel within ASME boiler codes and prevention of injury to personnel working in close contact with the pebble-bed structure. The design allowable pebble bed wall temperature selected is 390°K (250°F) or an overheat of 100°K from atmospheric conditions. The ASME boiler code allows a maximum mean wall temperature for carbon steel of 617°K (650°F) at the design stress level. The actual ASME design working temperature of 500°F (462°K) selected by SPARTA is conservative to ensure ample margins for safety.

6.2.1 Pebble-Bed Heater Wall Temperature

The pebble-bed pressure containment vessel wall is separated from the pebbles and their container by 0.05 m (2 inches) of ceramic blanket insulation to minimize heat transfer to the wall by conduction and radiation. A series of design calculations were performed to provide estimates of the wall temperature during and after pebble-bed heatup and the resulting minimum required insulation thickness.

6.2.1.1 Wall Heat Up During Pebble-Bed Heatup

An expression for the temperature of a solid bounded by two parallel planes with the planes being brought to temperature at a constant rate (Ref [6], pg. 104) was used to estimate the pebble-bed wall temperature. The solution is taken at the midpoint of the

boundaries where by symmetry there is no heat transfer. An conservative assumption is made whereby little or no heat transfer takes place from the pebble-bed pressure shell outer wall to the air.

In order to validate the wall heating estimates, the solution was compared to exterior wall temperature data taken from the 1/48th scale tests. It was necessary to select a value for the insulation thermal conductivity which was uncertain to a factor of three because only atmospheric pressure conductivity data was available. The pebble-bed exterior wall linearized heating rate calculated using polynomial linear regression techniques from 1/48th scale exterior wall temperature test data was determined to be approximately 35.0 °F/hr (19.0 °K/hr) and is plotted in Figure 6-4. The pebble-bed heat up rate was also taken from the same test bed interior temperature data and is plotted in Figure 6-5 (Reference [7]). A similar linear regression was performed and the heat up rate of the bed was determined to be approximately 380 °F/hr (210 °K/hr).

By comparison of 1/48th scale exterior wall prediction to the actual measured wall temperature data a conservative value of the insulation conductivity of 0.10 J/m/°K/sec was selected. Figure 6-6 shows wall temperature rise (above ambient) data versus time for 1/48th scale test and insulation thermal conductivities of 0.05 and 0.10 J/m/°K/sec.

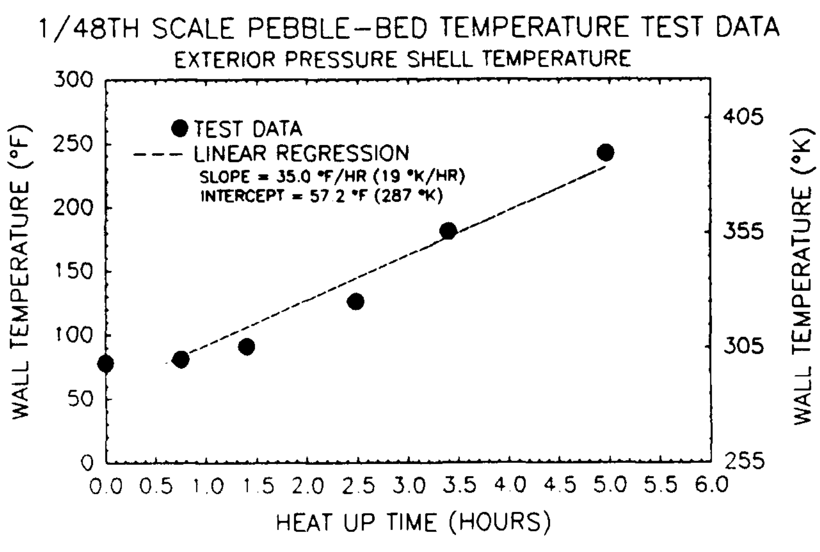

FIGURE 6-4 LB/TS 1/48TH SCALE EXPERIMENTAL DATA ON PEBBLE-BED EXTERIOR WALL HEAT UP.

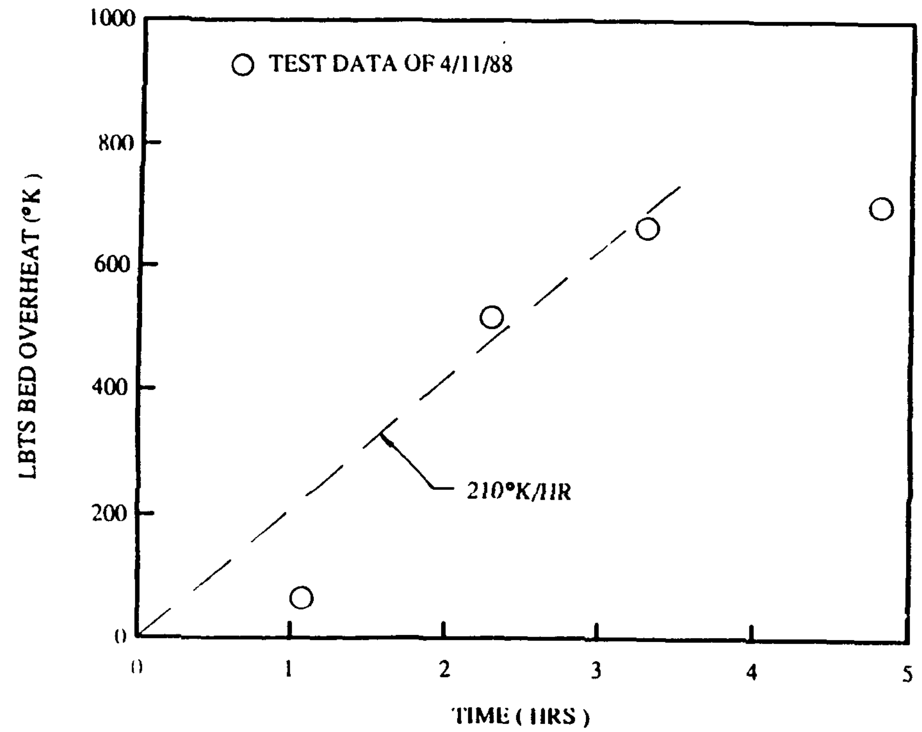

FIGURE 6-5 LB/TS 1/48TH SCALE PEBBLE-BED TEMPERATURE DURING HEAT UP.

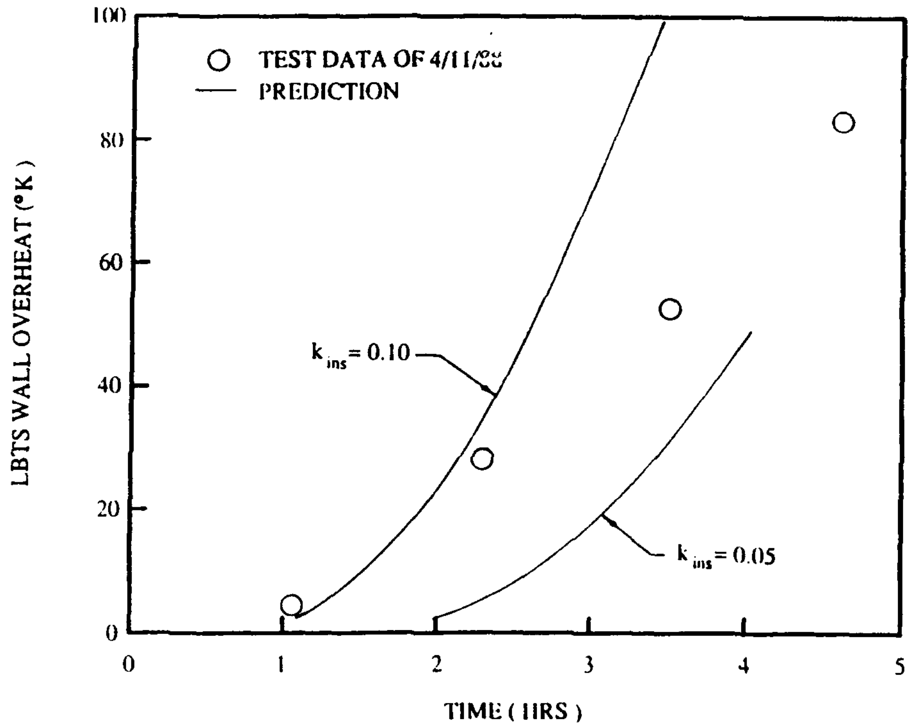

FIGURE 6-6 LB/TS 1/48TH SCALE PEBBLE-BED TEMPERATURE DURING HEAT UP.

The analytical technique validated for the 1/48th scale pebble-bed heating was then applied to the 1/6th scale pebble-bed design. The following equation predicts the exterior wall temperature of the pebble-bed heater:

$$Tw = C\cdot t - \frac{C\cdot l^2}{2\cdot K} + \frac{16\cdot C\cdot l^2}{K\cdot \pi^3}\cdot\sum_{n=0}^{\infty}\frac{(-1)^n}{(2\cdot n+1)^3}\cdot e^{\frac{-(2\cdot n+1)^2\cdot\pi^2\cdot K\cdot t}{4\cdot l^2}} \qquad \text{(EQ 6-3)}$$

where,

Tw, exterior wall temperature, °K
C, inner wall temperature increase (heating) rate, °K/sec
l, composite wall thickness, meters
t, time, sec
K, ratio of thermal conductivity to heat capacity, m^2/sec

$$\text{where,} \quad K = \frac{k}{\rho\cdot C_p}$$

k, thermal conductivity of composite wall, J/m/°K/sec
ρ, density of composite wall, kg/m^3
C_p, specific heat of composite wall, J/kg/°K

The pebble-bed pressure vessel design has a composite wall composed of an inner layer thickness, l_1, of insulation and an outer layer thickness, l_2, of steel. The composite wall property values are:

$$l = l_1 + l_2$$
$$l/k = l_1/k_1 + l_2/k_2$$
$$l\cdot\rho/\cdot C_p = l_1\cdot\rho_1\cdot C_{p1} + l_2\cdot\rho_2\cdot C_{p2}$$

In the SI (MKS) system of units:

Parameter	Units	Insulation (1)	Steel (2)
k	J/(m·sec·°K)	0.10	50
ρ	kgm/m^3	128	7800
C_p	j/(kgm·°K)	1000	450
l	m	0.026	0.046

The 1/6th scale pebble-bed design is similar to the 1/48th scale but has 0.10 m (4 inch) thick steel walls and the design heating rate is 340°K/hr which provides a bed temperature of 1360°K (2000°F) in 4 hours. Using 0.026 m (1 inch) of insulation limits the wall overheat (from ambient) to about 50°K in four hours as shown in Figure 6-7. Selection of 0.05 m (2 inches) of insulation reduces the overheat at four hours to under

10°K as shown in Figure 6-8. Both figures show the steel wall interior and exterior temperature rise over the 4 hour heat up time cycle.

6.2.1.2 Wall Heat Up After Pebble Bed Heatup

If the LB/TS test were to be delayed after pebble bed heatup but before filling the drivers, the wall of the pebble bed heater would continue to heat up due to conduction from the pebble bed. Some rather simple but indicative design analyses demonstrate that the 1/6th scale pebble bed overheat will decay exponentially with a time constant of 24, 36 or 48 hours depending on whether the insulation thickness is 0.025, 0.038 or 0.05 m. The wall will heat up with the same time constant in times short compared to the time constant. The design criteria of 100°K will be exceeded in 1 to 3 hours after pebble bed heatup depending on the insulation thickness as shown in Figure 6-9.

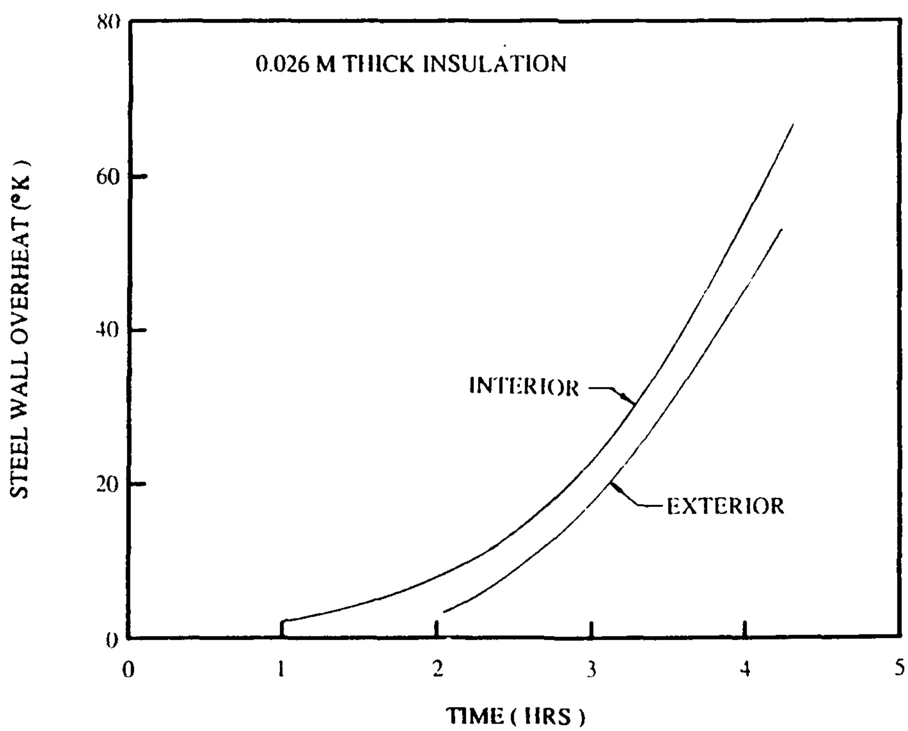

FIGURE 6-7 LB/TS 1/6TH SCALE PEBBLE-BED WALL HEATING DURING HEATUP CYCLE.

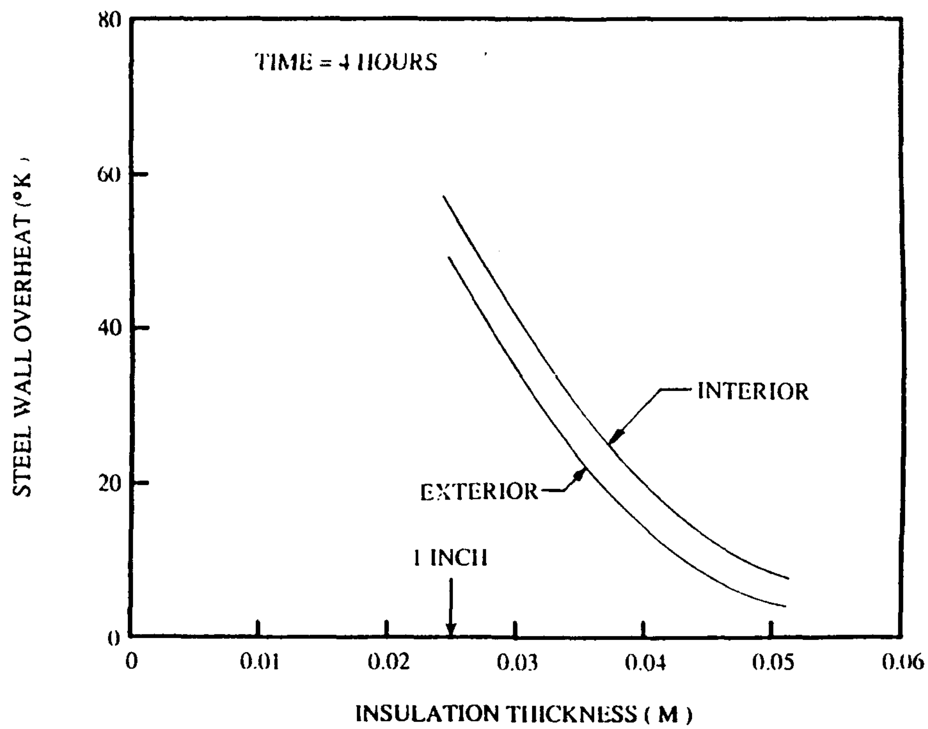

FIGURE 6-8 EFFECT OF INSULATION THICKNESS ON 1/6TH SCALE PEBBLE-BED EXTERIOR WALL TEMPERATURE.

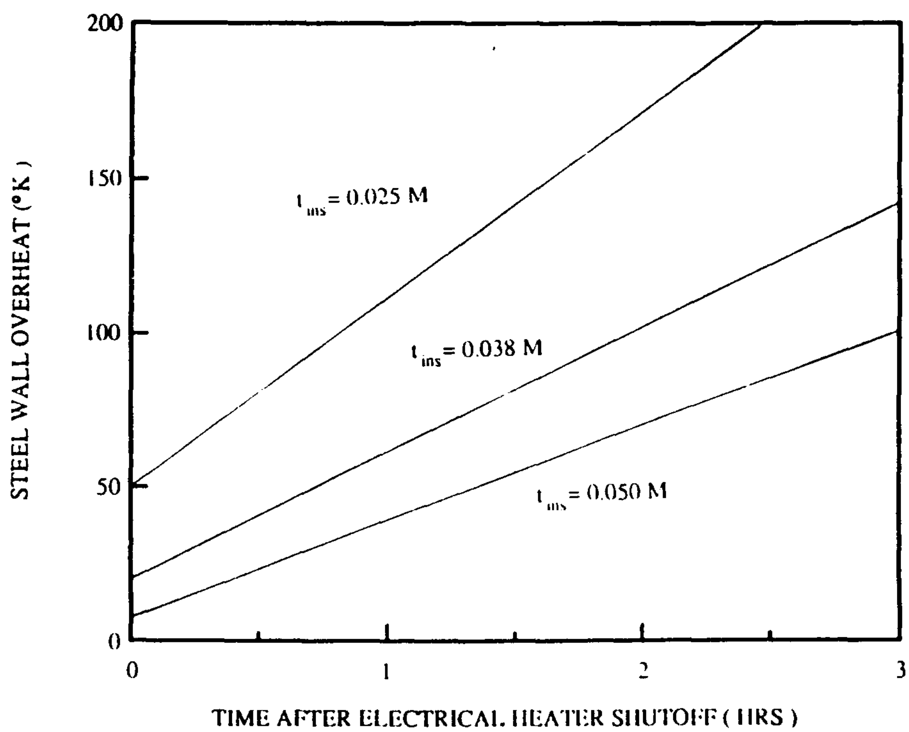

FIGURE 6-9 1/6TH SCALE PEBBLE-BED WALL TEMPERATURE AFTER BED REACHES 1360°K (2000°F).

If shocktube shots are to be suspended once the pebble-bed heater is fully charged. An active cooldown will be necessary to prevent outer wall temperatures from exceeding the design limits. A typical active cooldown system could use water fed into the pebble-bed and/or water sprayed on the external surface of the vessel wall.

6.3 Thermal Mixer Design

The thermal mixer is composed of two main components; the pressure shell and mixing bed. Other components include a LN_2 injection port and a hot gas outlet port.

6.3.1 Mixer Pressure Shell

The mixer pressure shell is a welded assembly which is composed of a number of standard fittings. The following is a description of each of the parts and their associated specifications and ratings:

1 each: 8 NPS (8.625" outlet OD), ANSI Class 1500 Weld Neck Flange
Bore Diameter: 6.875" - XX Heavy Wall
Flange OD: 19.00"
Bolting: 12 x 1 5/8" bolts on 15.50" bolt circle.
ASME material specification: SA-182 F316 Forged Stainless Fittings
ASME pressure rating: 2270 psig

1 each: 8 x 6 NPS (8.625" x 6.625" OD), Butt Weld Concentric Reducer
Bore Diameter: Schedule 160 Wall (6.813" x 5.189")
ASME material specification: SA-403 WPS316 Stainless Fitting
ASME pressure rating: Large End - 2427 psig
Small End - 3000 psig

1 each: 6 x 4 NPS (6.625" x 4.500" OD), Butt Weld Concentric Reducer
Bore Diameter: Schedule 160 Wall (5.189" x 3.438")
ASME material specification: SA-403 WPS316 Stainless Fitting
ASME pressure rating: Large End - 3000 psig
Small End - 3740 psig

1 each: 4" NPS Elliptical End Cap
Bore Diameter: Schedule 160 Wall
ASME material specification: SA-403 WPS316 Stainless Fitting
ANSI pressure-temperature rating: 3740 psig

1 each: 6 NPS ANSI Class 1500 Weld Neck Flange
Bore Diameter: 5.189" - Schedule 160 Wall
ASME material specification: SA-182 F316 Forged Stainless Fitting
ASME pressure rating: 2250 psig

1 each: 6 NPS Butt Weld Tee
Bore Diameter: 3.152" - XX Heavy Wall
ASME material specification: SA-403 WP316 Alloy steel fittings
ASME pressure rating: 3000 psig

6.3.2 Thermal Mixer Bed and Insulation Design

The mixer bed is much like the heater bed in appearance but performs a much different function. Figure 6-10 schematically shows the mixer assembly. The mixer bed consists of the same Ni-Resist balls as are used in the evaporator/superheater pebble-bed for ease in design although smaller diameter balls would be better here. The hot gas enters from the heater bed and cold gas or LN_2 is injected through the bypass gas adapter port and nozzle assembly. The distribution of the flow through the use of a spray nozzle and the mixer pebble-bed aid in efficiently mixing the hot and cold gases so that a uniform controlled gas outlet temperature is attainable at any desired flowrate.

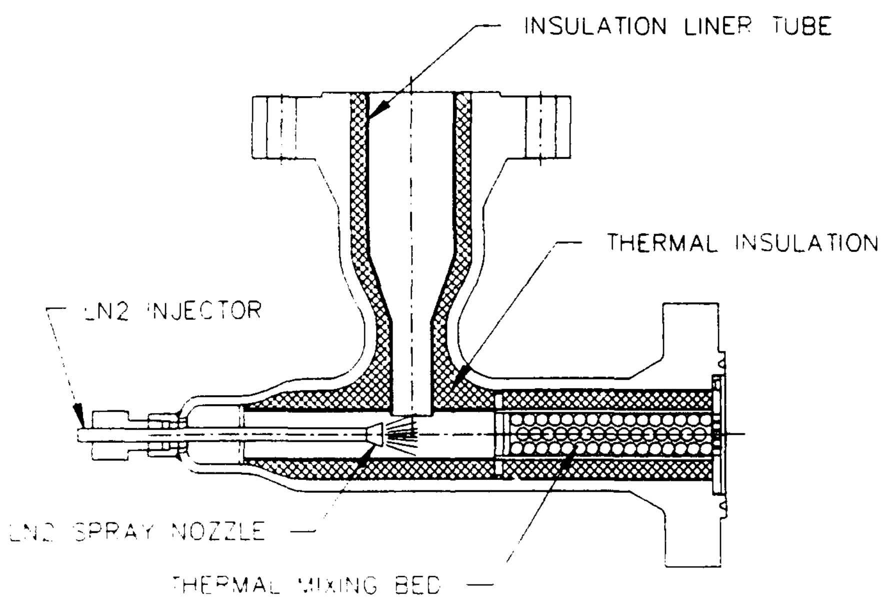

FIGURE 6-10 1/6TH SCALE THERMAL MIXER BED AND INSULATION DESIGN.

6.4 Electrical Thermal Charging System

The electrical thermal charging systems consists of 36 each of a 4.0 kilowatt electrical resistive heating element, a electrical power control system and a heater element temperature monitor/controller. The heater elements operate at 460/480 volts 3 phase alternating current and require a maximum of 144 kW (36 x 4 kW) of power. Figures 6-11 through 6-13 show electrical panel wiring schematics for the heater elements and the operating controls. Each panel controls 12 heaters and each can be indepentently operated to provide 1/3rd or 2/3rds of total thermal charging power.

The 36 heater elements are controlled through individual power relays and high limit temperature controllers. The controller limits the heater element to a preset value (1800 - 2000°F) and protects each element by turning it off when the maximum use temperature is exceeded. The heater elements are powered using a 3 phase 460/480 VAC delta circuit divided into three balanced legs. Three control panels are required with each panel controlling 12 heaters. The 3 phase power legs; L1, L2 and L3; are divided into three two leg combinations for each panel; L1-L2, L1-L3 and L2-L3. Each panel contains 5 terminal strips; two for 3 phase 480 VAC legs, one for safety ground, and two for 110 VAC line and neutral. The wiring for each panel is identical with only the 3 phase legs changing for each panel.

Temperature control is achieved through a high limit temperature controller circuit that monitors a type K thermocouple on each of the heater elements. The controller is set to the element maximum use temperature and turns the element off when that temperature is reached. These high limit controllers only provide a safety mechanism to prevent heaters from overheating and burning out. The bed temperature is manually controlled by monitoring the bed temperature, real time plotting the temperature distribution in the bed and manually turning off the heater power when adequate temperature distribution in the bed is achieved. A control relay can alternatively be used to turn all the heater power relays off using a control output from the data acquisition system and a computer control algorithm.

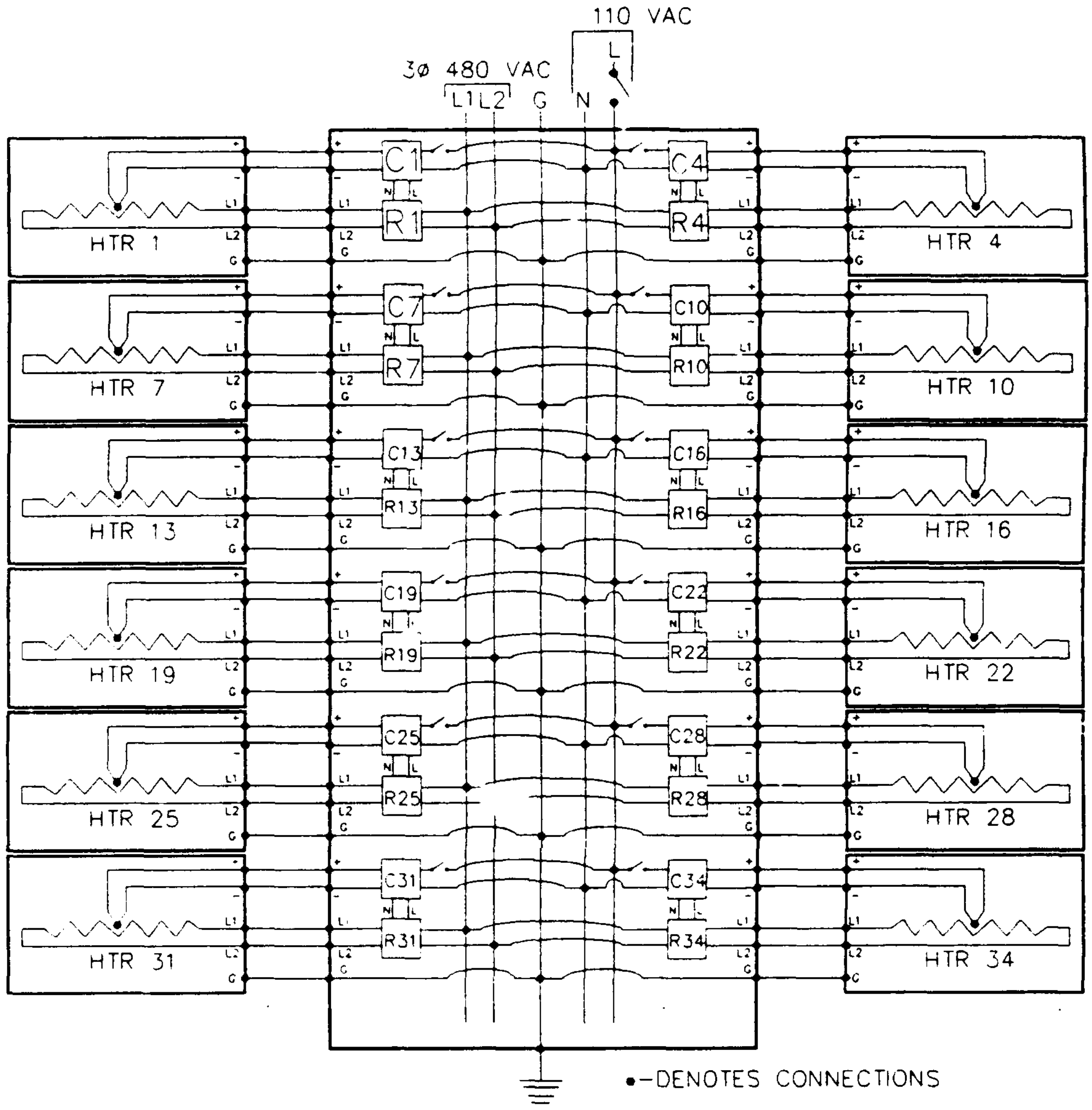

FIGURE 6-11 THERMAL CHARGING SYSTEM POWER DISTRIBUTION PANEL #1.

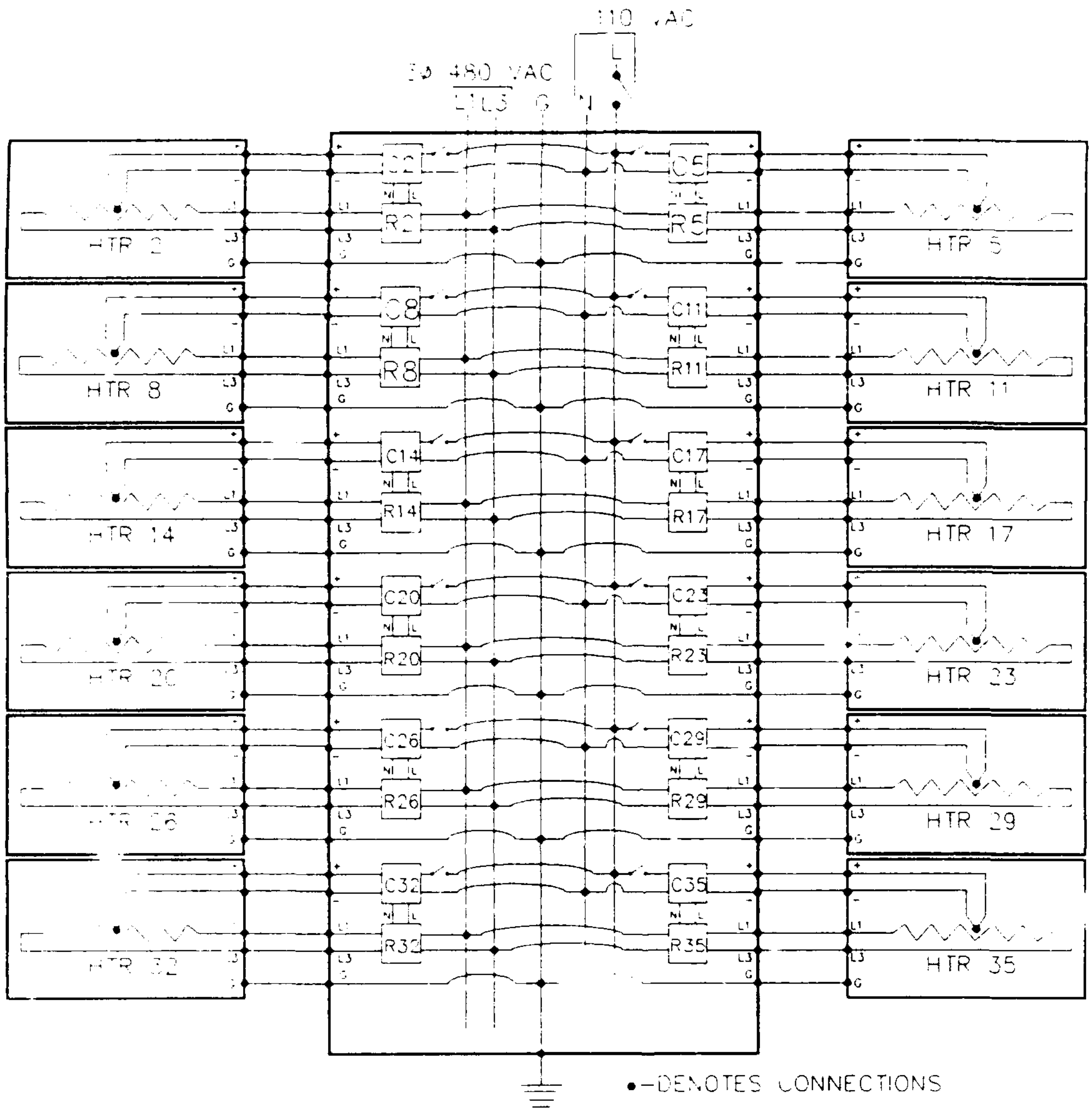

FIGURE 6-12 THERMAL CHARGING SYSTEM POWER DISTRIBUTION PANEL #2.

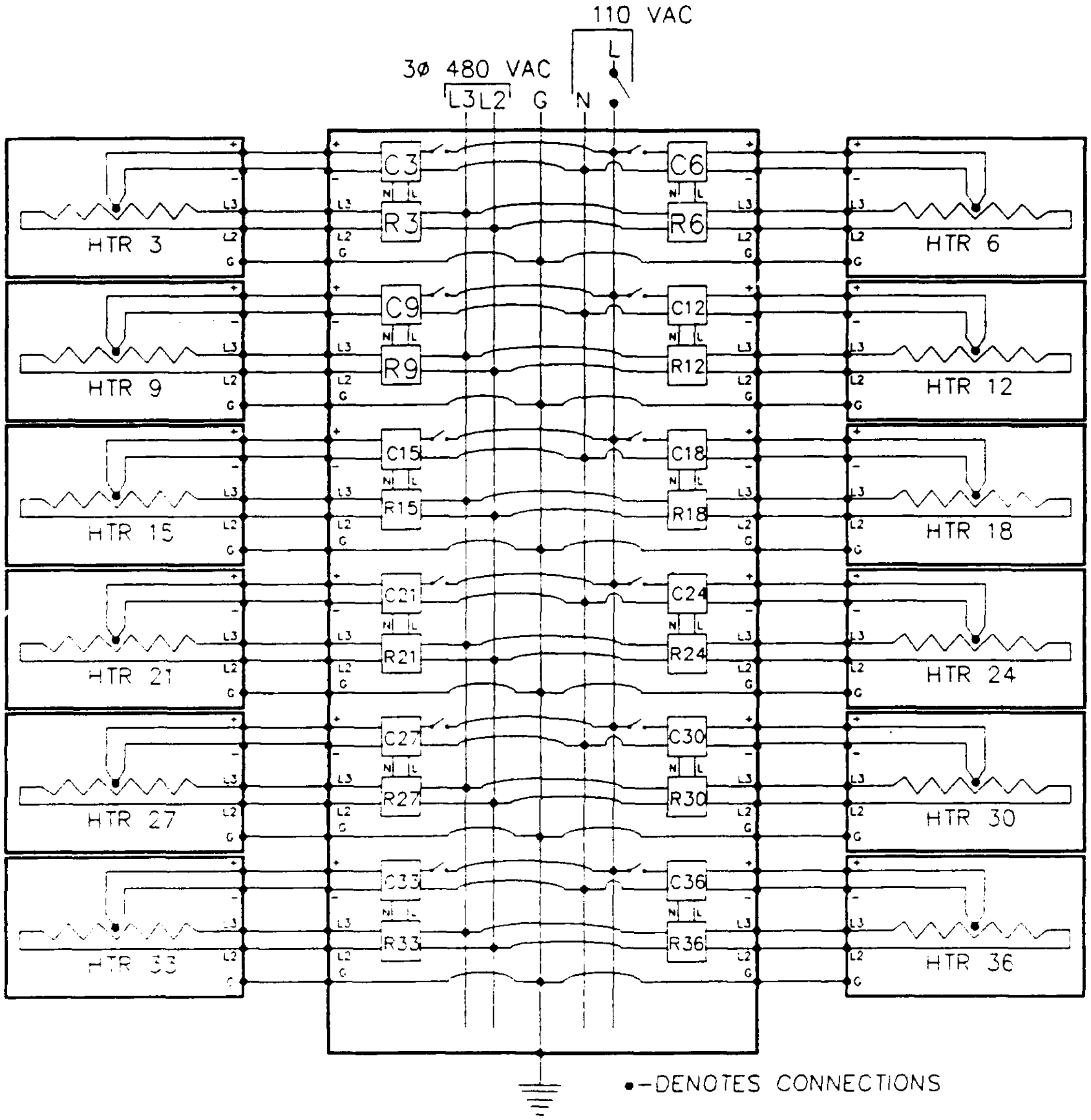

FIGURE 6-13 THERMAL CHARGING SYSTEM POWER DISTRIBUTION PANEL #3.

The specifications for the resistance heating elements are as follows:

Manufacturer:	WATLOW Electric Manufacturing Company
Model:	Firerod Cartridge Electrical Resistance Heater Element With high temperature seal.
Maximum Temperature:	2000°F
Voltage:	460/480 VAC
Power:	36 X 4000 Watts
Length:	108" overall
Unheated length:	2" bottom - 36" top (leads end)

The electrical heater elements specified for the 1/6th scale thermal charging system have a special pressure seal applied to the leads end to prevent air from entering the interior of the element. This seal would reduce the oxidation of the heating element material (nickel-chromium wire) at higher temperatures and thus permits a higher operating temperature. This offers an increase of 500°F (1500°F to 2000°F) over the 1/48th scale system and will provide approximately 60% more heat capacity to the system. As in the previous design, the heater elements are fed through the upper head assembly using high pressure compression fittings to facilitate ease in replacement should an element fail during service.

Each of the 3 power relay enclosures consist of the following components:

12 each:	2 pole power relays.
Rating:	DPST-NO, 30 resistive amps @ 460/480 VAC. 110/120 VAC control coil
12 each:	High Limit Temperature controllers, 0-1999°F normally open relays. 110/120 VAC power Type K thermocouple inputs. Thermocouple burnout (open circuit) opens control relay.
12 each:	Heater On/off switch with lamp status display. 110/120 VAC power, 1 switch per relay.
1 each:	120 VAC supply power switch Activates/deactivates all relays and controllers simultaneously.
12 each:	110/120 VAC - 15A fuse block and fuse.
12 each:	Outdoor rated plug socket for each heater element.
1 each:	Ground fault circuit interrupter relay.

A main 3 ϕ power distribution enclosure consists of 1 460/480 VAC - 300 AMP fused disconnect. Power distribution to the relay enclosures will be made using standard hard conduit systems rated for outdoor use.

Heater elements will be connected to the distribution enclosures by means of flexible cable rated for outdoor use and quick disconnect plugs and sockets also rated for outdoor use. Nominal conductor size for these 460/480 VAC extension cables will be 12 or 14 AWG. Type SO or SJO cable will be specified.

6.5 Hydrotests and Strain Measurement

Hydrostatic proof pressure tests will be performed on all 1/6th scale pressure components. Two pressure vessels will be fabricated and tested. The first hydrotest will be performed on the main heater bed pressure shell which will be manufactured from forged carbon steel. Its ASME design working pressure is 2200 psig at the design working temperature of 500°F. The second pressure vessel to be tested will be the thermal mixer shell that will be manufactured from type 316 stainless steel. Its ASME design working pressure is 2200 psig at the design working temperature of 850°F. Strain measurements will be made to validate the design stresses used in the pressure vessel structures design. Strain gage locations will be selected at the time of the tests.

According to the ASME code, Section UG-99 "Standard Hydrostatic Test", the hydrostatic test pressure is determined from the following relation:

$$P_h = P_d \cdot 1.5 \cdot \frac{SA_t}{SA_d} \qquad \text{(EQ 6-1)}$$

where,

P_h, Hydrostatic test pressure at all points in the vessel, psig
P_d, Design working pressure of the vessel, psig
SA_t, Allowable stress of the material at the test temperature, psi
SA_d, Allowable stress of the material at the design working temperature, psi.

The hydrostatic test pressure for the heater pressure shell is 3300 psig and for the mixer shell is 4000 psig. The difference is because the mixer is designed to operate at a higher temperature than the heater pressure shell.

6.6 Engineering Design Drawings

The following table is a list of the engineering drawings that SPARTA produced for the 1/6th scale pebble-bed evaporator/superheater system. A complete set of the 30 drawings was reduced to a 8 1/2 x 11 size pages and they are presented in a separate report entitled "Design Package for the Fabrication of the 1/6th Scale LB/TS Pebble-Bed LN_2 Evaporator/Superheater System". The design package report supplies copies of the drawings, a parts list, and a detailed cost estimate for the fabrication of the 1/6th scale pebble-bed evaporator/superheater driver gas heating and pressurization system.

TABLE 6-1 DESIGN DRAWINGS FOR THE 1/6TH SCALE PEBBLE-BED SYSTEM

	DWG NO.	DASH NO.	SHEET	DWG TITLE
1	PB88002		(1 OF 1)	PEBBLE-BED ASSEMBLY
2	PB88PI002		(1 OF 1)	PEBBLE-BED INSULATION ASSEMBLY
3	PB88MI002		(1 OF 1)	MIXER INSULATION ASSEMBLY
4	PB88LI002		(1 OF 1)	LINER INSULATION ASSEMBLY
5	PB88IB002		(1 OF 1)	HEATER THERMAL STORAGE BALLS
6	PB88HS002		(1 OF 7)	PRESSURE SHELL WELD ASSEMBLY
7			(2 OF 7)	BASE SUPPORT WELD ASSEMBLY
8		-1	(3 OF 7)	LOWER REVERSE FLANGE DETAILS
9		-2	(4 OF 7)	OUTER CONNECTING PIPE DETAILS
10		-3	(5 OF 7)	UPPER WELD NECK FLANGE DETAILS
11		-4,-5,-6	(6 OF 7)	BASE DETAILS
12		-7,-8	(7 OF 7)	LIFTING LUG DETAILS
13		-9	(1 OF 1)	UPPER BOLTED HEAD DETAILS
14		-10	(1 OF 1)	COVER FLANGE DETAILS
15	PB88MS002		(1 OF 3)	MIXER SHELL WELD ASSEMBLY
16			(2 OF 3)	END CAP BOSS DETAILS
17			(3 OF 3)	MIXER BILL OF MATERIALS/PARTS LIST
18		-5,-6	(1 OF 1)	MIXER SHELL FLANGE DETAILS
19	PB88ML002		(1 OF 3)	MIXER BED LINER WELD ASSEMBLY
20		-2,-3	(2 OF 3)	MIXER LINER DETAILS
21		-1,-4	(3 OF 3)	MIXER LINER DETAILS
22	PB88HB002		(1 OF 1)	HEATER BAFFLE WELD ASSEMBLY
23		-1	(1 OF 1)	FLOW BAFFLE PLATE #1 DETAILS
24		-2	(1 OF 1)	FLOW BAFFLE PLATE #2 DETAILS
25		-3	(1 OF 1)	FLOW BAFFLE PLATE #3 DETAILS
26	PB88HL002		(1 OF 1)	HEATER LINER WELD ASSEMBLY
27		-1	(1 OF 2)	LINER TUBE FABRICATION
28		-1	(2 OF 2)	LINER TUBE DETAILS
29		-2,-3,-4	(1 OF 1)	LINER FLANGE RING DETAILS
30	PB88HLB02		(1 OF 1)	HEATER LINER/BAFFLE ASSEMBLY

6.7 Parts List

A complete parts list was generated by SPARTA and is included in the assembly drawing for the pebble bed evaporator/superheater.

7. INSTRUMENTATION AND CONTROL SYSTEM DESIGN

The instrumentation for the 1/6th scale pebble-bed driver gas heating system measures temperature and pressure at various locations in the bed and along the LN_2/GN_2 flow path. Controls for the system at present are manual, but the valving components were selected based on their capability to be easily converted to automated control. It is recommended that automated controls be pursued with the pebble-bed to efficiently operate the pebble-bed system and reliably achieve desired driver conditions.

7.1 Measurement of Pressure and Temperature

Figure 7-1 gives the locations of all the instrumentation (thermocouples (T/Cs) and pressure transducers (PTs)), piping, and valving to be installed in the 1/6th scale LN_2 pebble-bed evaporator/superheater. The following list outlines the various components and their locations.

LIST OF INSTRUMENTATION

THERMOCOUPLES

INTERIOR OF THE PEBBLE-BED

TC 1-7	SECTION 1
TC 8-14	SECTION 2
TC 15-21	SECTION 3
TC 22-28	SECTION 4
TC 29-35	SECTION 5

HOT GAS FLOW

TC 45	PEBBLE-BED EXIT
TC 49	MIXER EXIT

THERMOCOUPLES (CONTINUED)

EXTERIOR PRESSURE SHELL
TC 36-44 PRIMARY SHELL
TC 46-48 MIXER SHELL

PRESSURE TRANSDUCERS

PT1	DIFFERENTIAL	PRIMARY BED FLOW
PT2	DIFFERENTIAL	BYPASS MIXER FLOW
PT3	GAGE	LN2 INJECTION INLET
PT4	GAGE	PEBBLE-BED INLET
PT5	GAGE	PEBBLE-BED MIDDLE
PT6	GAGE	PEBBLE-BED OUTLET
PT7	GAGE	MIXER OUTLET

VALVES AND FLOWMETERING

VALVES
IBV INLET LN2 BLEED VALVE
PGV PRIMARY BED LN2 GLOBE VALVE
PCV PRIMARY LN2 CHECK VALVE
BGV BYPASS LN2 GLOBE VALVE
BCV BYPASS LN2 CHECK VALVE
OBV OUTLET HOT N2 BLEED VALVE
OGV OUTLET HOT N2 GLOBE VALVE
OCV OUTLET HOT N2 CHECK VALVE

FLOWMETERS
PFM PRIMARY ORIFICE FLOWMETER (LN2)
BFM BYPASS ORIFICE FLOWMETER (LN2)

7.1.1 Temperature Measurement Grid

Pebble-bed internal T/Cs are grouped into 5 sections as shown in the figure. The angular and radial locations of the T/Cs with respect to heater element position #1 are given in the inset on the figure. Consecutive T/C's numbered 1-7 correspond to radial and angular locations A through G shown. The interior bed T/Cs measure actual bed temperature by attaching the thermocouple junction to a pebble or stainless steel mass equivalent of a pebble. This insures that the thermocouple will respond to changes in the bed temperature and not to local gas conditions if the T/C junction happens to not touch any of the bed material.

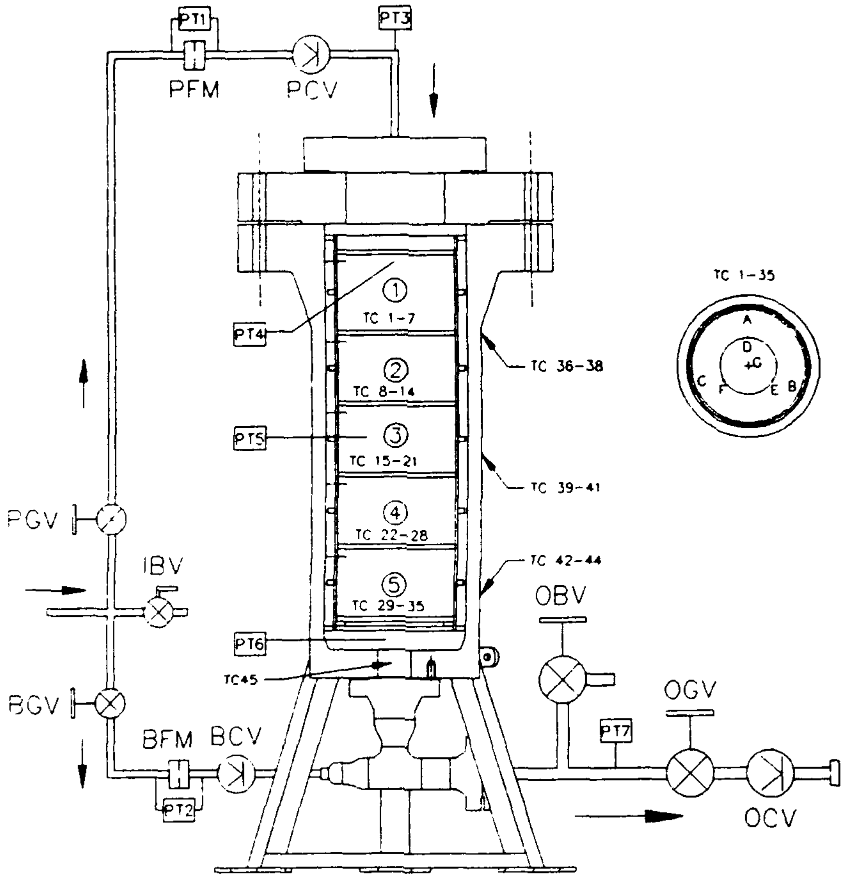

FIGURE 7-1 1/6TH SCALE PEBBLE-BED EVAPORATOR/SUPERHEATER SYSTEM INSTRUMENTATION, PIPING AND VALVING DESIGN SCHEMATIC.

Gas temperatures are measured by inserting the T/C junction into the stream of hot gas. This measures the static temperature of the gas. The T/C is located in a relatively large cross-section area flow passage to minimize flow velocity influence on the gas temperature (i.e. as velocity increases, static temperature decreases; for Mach 1 flow the static temperature is 83% of the stagnation temperature according to isentropic flow theory). A thermocouple at rest in the gas stream does not measure either the total temperature or the static temperature. It measures a temperature somewhere in between what is called the recovery temperature. Therefore, it is important to avoid regions of high velocity flow in placing thermocouples. The following relation gives the relation between the flow velocity (Mach Number) and gas temperature.

$$T_o = T_s*[1 + [(k-1)/k]*M^{\wedge 2}] \quad \text{(EQ 7-1)}$$

where:
T_o, total temperature
T_s, static temperature
k, gas ratio of specific heats
M, local Mach number

Temperatures on the exterior of the pressure vessels will be measured using a T/C junction welded to the metal surface at the locations indicated on the figure. Close monitoring of these external temperatures is important to safely operate the system.

7.1.2 Gage Pressure Measurement

Pressure measurement will be accomplished by electronic pressure transducers installed at several points along the flow path. Figure 7-1 shows the location of pressure transducers PT 1 through 5 which will be used to measure the pressure drop during LN_2 flow tests. PT 5 will be used to measure backpressure exerted by the driver during fill.

7.1.3 Differential Pressure/Flow Measurement

Flow measurements will be made using differential pressure transducers PT 6 & 7 and orifice plates mounted at positions FM 1 and 2 as shown in Figure 7-1. Because high pressure fluctuations might be present due to the LN_2 pump pulsations, the LN_2 reciprocating piston pump will be equipped with a pulsation damper. The orifice plates will be sized to impose a pressure drop from 25% to 75% of the maximum pressure condition depending on the flow rate and desired driver conditions.

The flow of LN_2 that travels through the primary inlet and mixer bypass portions of the system can be calculated if the total flow is known and the differential pressure through the identical orifice plates on flow meters are known. The flowrate through an orifice meter is proportional to the square root of the pressure drop across the orifice[8].

The flowrate in the primary inlet or bypass can be calculated from the following relations:

$$Q_i = C_1 \cdot \sqrt{\Delta P_i}, \quad \text{flowrate of primary inlet flow} \qquad \text{(EQ 7-2)}$$

$$Q_b = C_2 \cdot \sqrt{\Delta P_b}, \quad \text{flowrate of bypass flow} \qquad \text{(EQ 7-3)}$$

If the orifice plates and the gas/liquid properties are assumed to be identical at both flowmeters, then $C_1 = C_2$. From flow continuity, the primary inlet plus the bypass flowrates equals the total flowrate, Q_t, represented in the following relation:

$$Q_t = Q_i + Q_b \qquad \text{(EQ 7-4)}$$

The total flowrate is assumed known from the pump output and is calculated from the following relation:

$$Q_t = \pi/4 \cdot D^2_b \cdot S_p \cdot \epsilon_v \cdot R_p/C \qquad \text{(EQ 7-5)}$$

where,

Q_t, Total flowrate of LN_2, GPM
D_b, Piston bore diameter = 3 cylinders x 2.0 in
S_p, Piston stroke length = 1.3 in
ϵ_v, Volumetric efficiency of pump, assumed ≈ .87
R_p, Speed of the pump, RPM
C, Conversion factor = 231 in^3/gallon

Pump speed is determined by the electric drive motor speed and the drive pulley sprocket sizes on the pump and motor. The AC induction electric motor has a constant speed of 1770 RPM.

$$R_p = R_m \cdot T_m/T_p \qquad \text{(EQ 7-6)}$$

where,

R_m, motor speed = 1770 RPM
T_m, # Teeth on motor sprocket
T_p, # Teeth on pump sprocket

For a flowrate of 32 GPM, the pump speed should be 695 RPM. The resulting tooth ratio, T_m/T_p, is 0.39.

From a measured ΔP for the primary inlet and bypass flows, equations 7-1, 7-2 and 7-3 form a matrix of 3 equations with 3 unknowns, C ($C_1 = C_2$), Q_I, and Q_b and can be easily solved for the flowrates, Q_I and Q_b.

8. PRESSURE DROP ANALYSES

From the previous study and test program, the pressure drop was predicted in the 1/48th scale pebble-bed for a flowrate of 8 GPM. The 1/6th pebble-bed configuration is 4 times the flow area and 4 times the flow of the 1/48th scale configuration. It is sufficient to say that the pressure drop analyses for the 1/48th scale are the same for the 1/6th scale. In either case the analytical and experimental pressure drops were relatively small, ≈ 5%, of the maximum driver pressure condition and ≈ 3% of the LN_2 pump system pressure capacity.

9. CONCLUSIONS

The conclusions drawn from the results of this program are tabulated below:

1. The LN2 pebble-bed evaporator/superheater concept was experimentally validated under the previous program and provided a database from which the 1/6th scale testbed system can be designed to be a practical and feasible means of quickly and simultaneously pressurizing and heating gas for the 1/6th scale LB/TS testbed driver.

2. The 1/6th scale LN2 pebble-bed evaporator/superheater size is roughly 4 times that of the previous design and provides ample excess for holding and additional functions.

3. The design of the 1/6th scale pebble-bed heating system proved to be practical to fabricate and operate and is a cost effective alternative to insulating the interior of the driver or to heating the entire driver to the driver gas operating temperature.

4. The internal pressure drop of gas flowing through the LN2 pebble-bed evaporator/superheater is almost negligible (in the order of 100 psi at a flow rate of 53 lbs/min).

5. The internal heat transfer predictions that were used in the design of the LN2 pebble-bed evaporator/superheater were very conservative. Future designs of full scale pebble-beds require additional test data produced by the implementation of the 1/6th scale design.

6. The calculated predictions of heat transfer to the pressure vessel walls of the LN2 pebble-bed evaporator/superheater were verified in previous tests and provide a tool for designing the insulation system on the 1/6th scale pressure vessels.

7. The nickel-iron alloy (Ni-Resist) pebbles used in the LN2 pebble-bed evaporator/-superheater are a proven material in the LN_2 pebble-bed design. Materials other than Ni-Resist seem to be a suitable for the pebble-bed balls, however, tests should be performed before use in the 1/6th bed is considered.

8. Aluminum oxide balls are cost effective alternative to the nickel-iron balls currently used. Cost savings as much as $26,000 for the 1/6th scale pebble-bed and $1.26M for all full scale units can be realized if alumina is validated for use in this pebble-bed application.

10. RECOMMENDATIONS

The following are recommendations for further development and testing of the pebble-bed system for use in the LB/TS.

1. Proceed with the fabrication of the 1/6th scale LN_2 pebble-bed evaporator/superheater system. Install and checkout the system at the BRL LB/TS testbed site.

2. Investigate alternative pebble materials by means of simple heating and LN_2 rapid cooling cycling tests on candidate materials. Positive results could provide up to 1/3rd the cost of pebble-bed materials on the 1/6th scale as well as the full scale pebble-bed heating systems.

3. Design, fabricate and test an automated exit gas temperature control system which automatically regulates the flow of LN_2 into the mixer to maintain the exit gas temperature at predetermined set point values.

4. Design, fabricate and test an automated exit gas pressure control system which automatically regulates the flow of LN_2 into the pebble-bed evaporator/superheater and mixer to maintain the driver pressure at predetermined set point values.

5. Design, fabricate, instrument and install a short horizontal length of simulated driver to investigate heat transfer from the rapidly filled gas to the driver wall. Typical tests would pressurize the simulated driver with gaseous N_2 heated to predetermined temperatures and measure the internal gas temperature and the pressure vessel wall temperatures as a function of time to obtain accurate values of the Grashoff number so that heat losses to the 1/6th scale and full scale LB/TS drivers can be calculated with higher confidence in view of the present lack of applicable test data. A coating of plasma sprayed ZrO_2 on half of the interior of the simulated driver could provide insight into the affectivity of plasma sprayed insulation. The 1/48th scale pebble-bed system can be used for these tests or even the 1/6th scale unit if available.

6. Perform 1/6th scale LN_2 tests at the SPARTA test site to increase the database of temperature and flow data so as to enhance and optimize present pebble-bed sizing and modeling methods. This wealth of data would increase design confidence, reduce margins of uncertainty and reduce costs of future full scale units. Additionally, test the 1/48th or 1/6th LN2 pebble-bed evaporator/superheater for its use in providing gas outlet temperatures ranging from 70°F (530°R)

to 800°F (1,260°R) and at exit pressures ranging to 2,000 psig. A pebble-bed gas supply system can provide high flow room temperature gas for the TRS combustion products ejection system or other systems requiring high pressure gas at temperatures ranging to 850°F.

7. Provide a complete 1/6th scale automated driver pressurization system that is controlled and monitored by a single computer system. The system would be turn-key operation only requiring pressure and temperature setpoints to actuate. Safety features such as emergency cooldown or driver venting could be automated and provide manual override. The system can be easily integrated with other testbed LB/TS systems such as the wave shaping valve and the rarefaction wave eliminator systems.

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